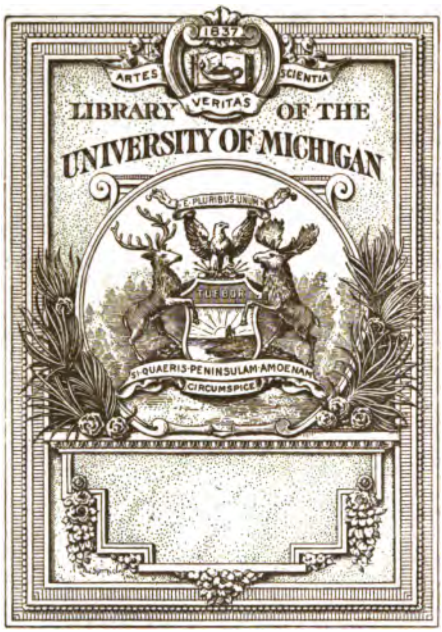
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STUDIES IN TERRESTRIAL MAGNETISM

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STUDIES IN TERRESTRIAL MAGNETISM

BY

C. CHREE, M.A., F.R.S.

SC.D. (CAMB.), LL.D. (ABERDEEN)

Superintendent of Kew Observatory

Late Fellow of King's College, Cambridge

Ex-President Physical Society of London

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PREFACE

A SHORT statement seems desirable as to the object of the present book. The volume does not aim at being a text-book of Terrestrial Magnetism, or at summarising existing knowledge in those branches of Terrestrial Magnetism with which it deals, but is intended to give a connected account of my own original work in that subject, referring to the work of others only so far as is necessary for intelligibility. It is hoped that other investigators will understand that the absence of reference to their work implies no lack of appreciation of its value.

Again, while I have worked at several of the more important branches of Terrestrial Magnetism, there are other branches which I have scarcely touched on, if at all. The subject of Terrestrial Magnetism is very large and ever-increasing; and the contributions made to it by any one individual must form but a small fraction of the whole.

The book deals almost entirely with facts, or supposed facts. The absence of a definite theory as to the origin of the several magnetic changes is due to no lack of curiosity as to the causes of things, but to a belief that at the present stage theorising is less likely to be of substantial advantage than the extension of positive knowledge. It is sometimes claimed that a theory is essential as a guide in selecting the directions in which to

prosecute research. This is a very partial truth. When a man devotes himself to a subject, allowing free ingress to his mind to all the ideas which the results obtained by investigators naturally suggest, he must be a very unimaginative person if profitable lines of enquiry do not force themselves on his intelligence. The difficulty is not in thinking of something to do, but of deciding what to do next. In making a choice, some may prefer the guidance supplied by a definite theory, but others will prefer to rely on their natural instinct for detecting a weak spot in the defence offered by Nature to the discovery of her secrets.

Those who are familiar with the additions made during recent years to our knowledge, by the discovery of ionisation and radioactive processes, and by investigations on electrical discharge in high vacua, will, I think, allow that speculations made even twenty years ago as to the origin of the phenomena of Terrestrial Magnetism laboured under great disadvantages. But to the average physicist twenty or even ten years hence, the ablest physicist of to-day may seem just as poorly equipped for theorising on Terrestrial Magnetism as the speculators of twenty years ago now seem to us.

Another consideration is that the phenomena of Terrestrial Magnetism are of a complicated nature. The so-called regular daily changes vary largely with the season of the year, and from one year to the next; the so-called irregular changes are multitudinous. We can scarcely hope that in our time any general theory will present a satisfactory explanation of all observed facts, or enable us completely to forecast the future. For, at least, a long time to come, it is to observation, not theory, that we must look for detailed knowledge, and it is in any case to observation that we must turn as the touchstone by which to try theory.

I am indebted to the President and Council of the Royal Society for permission to reproduce a variety of diagrams and curves which have appeared in the *Philosophical Transactions*, and in particular for permission to make and reproduce copies of a number of magnetic disturbances recorded in 1902–3, which were originally discussed in the volume of the *National Antarctic Expedition* 1901—1904: *Magnetic Observations*, published in 1909 by the Royal Society. I am also indebted to the Meteorological Committee and the Director of the Meteorological Office for permission to reproduce copies of Kew magnetic curves.

My thanks are due to Prof. R. A. Gregory, the Editor of this series, for valuable assistance in revising the proof sheets and for many useful suggestions, to the Printers for their care and the skill with which they accommodated the text to the numerous tables and illustrations, and finally to Mr. Emery Walker and his staff for the trouble which they took, especially in dealing with the curves of magnetic disturbance—many of them faint and difficult objects—and in reducing to a common time scale those forming the compositefigures in Chapter XIII.

CHARLES CHREE.

CONTENTS

CONTENTS

LIST OF ILLUSTRATIONS

STUDIES IN TERRESTRIAL MAGNETISM

CHAPTER I

MAGNETIC RECORDS

THIS book is mainly concerned with results derived from magnetograms, *i.e.*, curves from self-recording magnetographs. It is thus desirable to preface an explanation sufficient to enable the reader to understand how the records are obtained and interpreted.

In Fig. 1 disregard for the moment the line AB. Let MR represent the section by the plane of the paper—supposed horizontal—of a mirror capable of rotation about a vertical axis in its plane through O. A horizontal ray of light incident on MR in the direction LO is reflected along OP, intersecting at P ($OP = c$) a vertical plane perpendicular to OP. If now the mirror turns through a small angle i into the new (dotted) position $M'R'$,

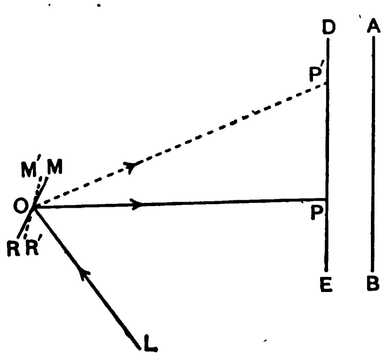


FIG. 1.

the reflected ray will take the new (dotted) position OP', and by a well-known optical principle the angle

POP' through which the reflected ray is rotated is double the angle i through which the mirror has turned. Also we have:

$$P'P = OP \tan P'OP = c \tan 2i,$$
$$= 2ci \text{ for small values of } i.$$

If then we know c, and measure $P'P$, we determine i from the equation:

$$i = P'P/2c.$$

If the mirror went on turning, now in one direction now in the other, the spot of light would move to and fro along the single line DE.

Suppose now DE to be a sheet of photographic paper, protected from all light except that reflected from the mirror. If we developed the paper we should get a single black line, the length of which would depend only on the two extreme positions assumed by the mirror while the paper was exposed to the reflected light.

Suppose, however, that the photographic paper is in a vertical frame, and that the frame travels downwards in its own plane—being actuated by clockwork—at a uniform rate, and suppose that, as the frame moves, a straight line is drawn representing the successive positions of the point P. When the paper is taken out of the frame, developed and spread out flat in a horizontal plane, it will show (Fig. 2) a straight line P_oP_q representing the successive positions of the point P in Fig. 1, and a wavy line $P'_oP'_q$ representing the successive positions of the point P'. If the frame has moved a distance d per hour, then if we measure off $P_oP_n = nd$, and through P_n draw D_nE_n perpendicular to P_oP_q, D_nE_n represents the line DE of Fig. 1, n hours from the start, and P'_n represents the corresponding

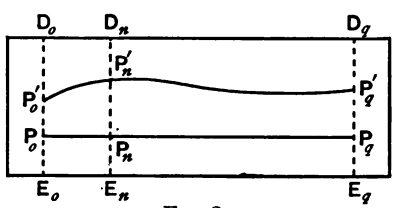


FIG. 2.

position of P'. Thus the value of the angle i at hour n is obtained by dividing P'_nP_n by $2c$.

In the original Kew magnetograph, as devised by Sir Francis Ronalds, the sensitised surface was a flat metal plate in a frame, and the frame was actually drawn along by clockwork in the way supposed. The present form—due to Sir Francis' successor, Mr. John Welsh—and most if not all modern magnetographs employ photographic paper, wound on a cylindrical drum. The line AB in Fig. 1 is intended to represent the (horizontal) axis of this drum. The paper on which the reflected light falls is obviously moving at the instant vertically, and the rate is uniform if the drum rotates uniformly.

In a magnetograph the mirror MR is attached to a magnet (in the case represented in Fig. 1 this magnet would be horizontal, and would represent either the declination or the horizontal force magnet), and the angle through which MR turns, and which the curve allows one to measure, is the angle through which the magnet has turned from a fixed position. The line answering to the fixed point P in Fig. 1—*i.e.* the line P_oP_q of Fig. 2—is actually obtained by reflecting light, originating from the same source L, from a fixed mirror adjacent to the mirror carried by the magnet. Further, for convenience in marking the time, the light from the fixed mirror is interrupted every two hours, the interruption being effected by a stop actuated by the clockwork which turns the drum. In the Kew magnetograph the stop comes on at four minutes before the hour and goes off at the hour.

The paper is held in its place on the drum by clamps. The drum is arranged to turn completely in twenty-five hours or more; thus the complete length of the photographic sheet represents appreciably more than the travel of the paper in twenty-four hours.

At Kew the same sheet remains on the drum for forty-

eight hours. At the end of the first twenty-four hours the source of light is moved from one fixed position to another. This is equivalent to moving P and P' (of Fig. 1), through a fixed distance along the line DE. During the short time requisite for moving the light, and for bringing round the drum approximately to its original position, the paper is shaded. Fig. 3 shows on a reduced scale records of Kew horizontal force during two successive days. The base lines are easily recognised by the time breaks every two hours. The upper base line and the upper curve line answer to one another and belong to the

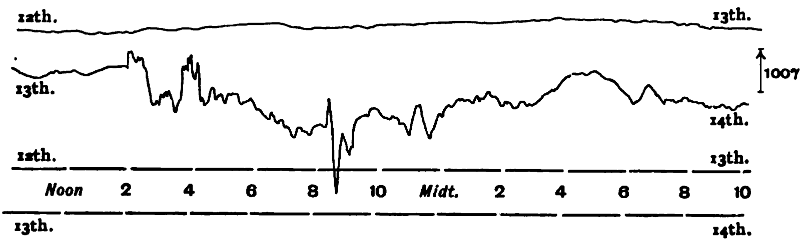


FIG. 3.—KEW HORIZONTAL FORCE. NOVEMBER 12–14, 1894.

first "day," which commenced a little after 10 a.m. on November 12th, 1894, and ended shortly after 10 a.m. on the 13th. The second day's record commenced a minute or two after this, and lasted until after 10 a.m. on the 14th.

The first day's trace in Fig. 3 represents a magnetically quiet day. The fluctuations in the ordinate of the curve, and so in the angle between the fixed mirror and that attached to the magnet, are neither large nor rapid. After 2 p.m. on the second day the curve changed in character, showing large oscillations, a condition generally described as a "magnetic storm."

The magnet of the horizontal force magnetograph is supported at Kew by a bifilar suspension (a stout quartz fibre is substituted in some instruments). The torsion head, to which the suspension is attached, is turned until

the magnet is at right angles to the magnetic meridian, and it would naturally remain in that position if nothing altered, the position answering to a balance between the magnetic couple tending to bring the magnet back into the magnetic meridian, and the torsion couple tending to move it away from the meridian. When, however, the horizontal force begins to vary, the magnetic couple prevails if the force increases, while the torsional couple prevails if the force diminishes. The magnet with its attached mirror thus turns the one way or the other according to the variation of the magnetic force, and the reflected spot of light moves to right or left in the horizontal plane (see Fig. 1). Movement up the page in Fig. 3—or, as it is usually described, up the *sheet*—represents increase of the magnetic force, and movement down the sheet decrease. To obtain a numerical estimate of the change of force, one measures the change in ordinate corresponding to a definite change of force produced artificially, *e.g.*, by means of a magnet of known moment at a measured distance. When the suspension is bifilar, one can alter the scale value by altering the distance between the suspension fibres. The value maintained at Kew—and that most generally adopted—is :

$$1 \text{ cm.} = 0{\cdot}00050 \; C.G.S. = 50 \; \gamma,$$

where 1γ is used to denote 1×10^{-5} *C.G.S.* unit.

In the case of the declination magnet the suspension is unifilar and aims at being torsionless. The magnet remains in the magnetic meridian, and its movements and those of the attached mirror thus show changes in the azimuth of the magnetic meridian, *i.e.* changes of magnetic declination. The scale value in this instance is determined by the distance between the magnet's mirror and the photographic paper.

The third element recorded is the vertical component of force. In this instance the magnet is supported on

a knife edge, which rests upon agate. Rotation about the knife edge is equivalent to rotation of the magnet in a vertical plane about a horizontal axis, so that the spot of light reflected from the attached mirror describes a vertical line. At stations where the north pole dips, the north pole moves downwards or upwards according as the vertical force increases or diminishes. The axis of the drum on which the photographic paper is wound is in this instance vertical, so that the circumstances are really the same as for the two other elements, and the three traces present the same general features. The three drums are driven by one clock, so that any uncorrected clock error affects the three traces equally.

In the Kew magnetographs the paper travels approximately 15 mm. in the hour, *i.e.* the interval between successive 2-hour breaks in the time line represents in the original curves 30 mms. With this time scale—*i.e.* 4 minutes to 1 mm.—the accuracy with which the time of any particular movement on the trace can be fixed is not very high, especially when the movement is small and represents a slow change of force. Occasionally one has a large change in one direction in the course of a few minutes, or a sudden change from a rapid rise to a rapid fall, or conversely. Examples are afforded in Fig. 3 by the sudden rise of force on November 13 a little after 2 p.m., and by the turning points in the large oscillations between 8 and 10 p.m. In such circumstances one may reasonably expect to fix the time of commencement or of change of direction of motion to within a minute.

An arrangement for rotating the drum at a specially rapid rate is usual in modern magnetographs. At Kew the high speed is twelve times the ordinary, giving 3 mm. to one minute. The time answering to any given point on the curve can then be assigned with much greater precision, and oscillations of force of short period are

shown which could not be recognised on ordinary curves. Quick-run curves, however, do not possess all the advantages one might at first suppose. An increased openness of time scale reduces in the same proportion the gradient of the curve. Thus movements of small amplitude and no great suddenness do not readily appeal to the eye. To reap the full advantage of increased openness of time scale, one requires also to increase the sensitiveness of the instrument, so as to get an increased difference of ordinate for a given change of force. It must, however, be remembered that increased sensitiveness, unaccompanied by increased width of the photographic paper, means increased risk of the trace going beyond the limits of registration. As a rule, quick runs are confined to special prearranged hours when some international research is in progress.

Some magnetographs, *e.g.* those of the Eschenhagen pattern used in 1902–4 at the Winter Quarters of the National Antarctic Expedition—curves from which will be shown later in the book—have only one drum and record the three magnetic elements on a single sheet of paper.

A knowledge of the ordinate scale value enables one to tell the difference between the values the element possesses at any specified times. But to tell the *absolute* values one must have recourse to the absolute instruments. Suppose, for instance, that the Kew unifilar magnetometer gives 16° 2′·0 for the declination at 2 p.m. on a certain day. One measures the ordinate of the curve at 2 p.m. and finds it to be, say, 50·2 mm. In this instrument 1 mm. represents 0′·87. Thus the base line value—*i.e.* the value which the declination would have if the curve came down to the base line—is 16°2′·0 less (50·2 × 0′·87), or 15°18′·3, to the nearest tenth of a minute. Accepting this determination, we know that if e represent the curve ordinate in mm. at any instant, the corresponding declination is $15°18'{\cdot}3 + e \times 0'{\cdot}87$.

In the case of the declination magnetograph the base line value should vary little if at all throughout the year. In this respect it possesses a marked advantage compared with magnetographs recording force components. In their case any change in the moment of the magnet—whether through lapse of time or temporary change of temperature—alters the base line value. An allowance is necessary for temperature change, and standardization of the curves is a good deal more troublesome than in the case of the declination, though the general principle is the same.

It is hoped that the explanation here given will suffice for a general understanding of the curves, but it omits reference to a variety of details which have to be taken into account by those in actual charge of magnetographs. Figs. 1 and 2, it should be added, are not drawn to scale, and Fig. 1 does not show lenses and other optical and mechanical details.

CHAPTER II

SECULAR CHANGE

EVERY educated man knows that the values of the magnetic elements at any given spot of the earth's surface are perpetually changing, but few realise the difficulty attaching to the *accurate* determination of secular change, or of the uncertainties prevailing in published values, especially those of some of the elements.

The uncertainties are largely of instrumental origin; but the stations where uncertainties are least are not necessarily those provided with the best and most expensive instruments. The man who is always "improving" his apparatus and methods may be a valuable asset to the world at large, but he is not unlikely to provide secular change data of less accuracy than those of his unprogressive neighbour whose methods and apparatus are second rate but as unalterable as the laws of the Medes and Persians.

Change of instrument or of method generally means change in the absolute value obtained for the element concerned, and unless this change is exactly determined and allowed for—usually a very difficult and tedious business—there is consequent error in the secular change.

Declination (D) is the element the determination of which presents the smallest opportunity for variable instrumental errors, and the observation itself is so simple that the probable observational error is trifling. Further, the differences between the values supplied for the declination

by different magnetometers are usually small, so that the introduction of a new instrument is unlikely to produce a large error in the secular change.

Horizontal force (H) usually comes next in order of certainty. The main source of instrumental uncertainty is in the value accepted for the moment of inertia of the collimator magnet, and with ordinary care *change* in the consequent error is likely to be very slow. The values, however, obtained from year to year for the secular change of H are usually notably less regular than the corresponding values for D, and the irregularities seen at neighbouring stations are often conspicuously dissimilar. It is thus reasonable to attribute them in considerable measure to instrumental or observational defects.

Inclination (I) presents some special features. The use of inductors is extending, and if the claims put forward for these instruments should be justified, and if they are not liable to serious deterioration with age, the uncertainties now existing in secular changes of inclination may be materially reduced in the near future. At the present moment, however, the great majority of stations use dip circles, and the behaviour of a dip circle depends largely on the condition of the dip needles, which is rather liable to change. There are, in fact, few, if any, stations at which records of dip do not present features which suggest instrumental vicissitudes.

Vertical force (V) is not as yet determined directly, but is calculated from observed values of horizontal force (H), and inclination (I) by the formula:

$$V = H \tan I.$$

Thus V suffers from whatever uncertainties affect either H or I. At Kew an error of 10γ in H or of $0'\cdot\dot{6}$ in I produces an error of 24γ in V. It is thus scarcely necessary to say that the secular change of V is usually exposed to considerably larger uncertainties than that of

H, and a similar remark applies to the secular change of total force (T).

The magnetic conditions at a place may be defined by D, I and either H, V or T; they may also be defined by three rectangular components such as V, N (north component) and W (west component).

The interrelations between these quantities are as follows:

$$N/\cos D = W/\sin D = H,$$
$$H/\cos I = V/\sin I = T.$$

By secular change from one year to the next is usually meant the difference between the mean values obtained for the element in question for the two successive years, and this is the sense accepted in Table I. Thus defined, the secular change depends for its accuracy on that of the mean annual values. The most perfect annual value of an element is that obtained by taking a mean from hourly measurements of the curves throughout the whole year, the base values of the curves being determined by the absolute observations. Most stations, however, omit the curves of highly disturbed days, and some measure only a selected number of curves. Thus at Kew and Falmouth the mean annual values are based on hourly measurements confined to five magnetically quiet days a month. At stations unprovided with magnetographs, the mean annual values are derived simply from the absolute observations.

When mean annual values are derived from quiet days only, it is not safe to assume that they will be absolutely the same as if they were derived from the curves of all days. In the case of D, direct comparison has shown both at Kew and Greenwich that mean annual values derived from five quiet days a month are unlikely to differ from those derived from all but the most highly disturbed days by more than $0'{\cdot}1$. In the case, however, of H, it has been found both at St. Petersburg and Green-

wich that there is a systematic difference between annual means derived from all and from quiet days, the latter being numerically the larger, and the average excess at both stations being about 3γ. If this difference is an absolute constant, its existence is immaterial so far as secular change is concerned. But if, as is more likely, it is not constant, secular changes—especially those for single years—got out from all and from quiet days will not be identical. This source of uncertainty is, however, comparatively trifling.

When annual values are derived from absolute observations only, the uncertainties may be more serious, even supposing the absolute observations to be made at regular intervals throughout the year and at fixed hours of the day. Suppose, for instance, the mean annual value of D at Kew had been derived from absolute observations made the whole year round at 2 p.m. At this hour the declination magnet is to the west of its mean position, to an extent which on the average day of the year varied from about $4'\cdot0$ in 1890 to about $6'\cdot3$ in 1893, and then to about $3'\cdot8$ in 1900. Thus the total secular change obtained between 1890 and 1893 would have been about $2'\cdot3$ too small—as D is falling—while that deduced between 1893 and 1900 would have been about $2'\cdot5$ too large. Again, while the average error in the secular change for a single year taken irrespective of sign would have been under $0'\cdot5$, it would for the year 1891–2 have amounted to nearly $1'\cdot4$. This error, it need hardly be pointed out, would not be even reduced by applying a correction to absolute observations based on a diurnal inequality derived from an entire eleven-year period, ignoring differences between individual years.

A great many of the earlier secular change data are based entirely on absolute observations. It is thus important to notice that provided these were taken at a fixed hour of the day this source of uncertainty becomes

trifling in the case of *mean* values of secular change derived from a *long* period of years. The uncertainty is not serious even for periods as short as three or four years provided the centre of the period falls either at sunspot maximum or sunspot minimum. The significance of these remarks will be more fully realised after a study of Chapter XIV.

TABLE I.—*Secular Change.*

Period.	Place.	*D.*	*I.*	*H.*	*V.*
		′	′	γ	γ
1860-1865	Kew	-8·0	-2·2	+22	-26
1865-1870	,, ...	-8·1	-2·0	+26	-11
1870-1875	,, ...	-8·5	-2·0	+25	-13
1875-1880	,, ...	-8·7	-1·2	+12	-16
1880-1885	,, ...	-6·6	-0·9	+18	+12
1885-1890	,, ...	-5·7	-1·1	+21	+11
1890-1895	,, ...	-6·8	—1·8	+22	-12
1895-1900	Greenwich ...	-5·7	-1·5	+25	+ 7
	Kew	-4·8	-2·7	+30	-16
	Stonyhurst ...	-5·4	-1·8	+33	+17
	Falmouth ...	-5·1	-3·0	+28	-40
	Mean	-5·2	-2·3	+29	- 8
1900-1905	Greenwich ...	-3·8	-2·5	+15	-54
	Kew	-4·0	-1·6	+16	-16
	Stonyhurst ...	-3·5	-0·8	+11	0
	Falmouth ...	-4·1	-1·8	+12	-36
	Valencia ...	-4·3	-1·8	+12	-39
	Mean	-3·9	-1·7	+13	-29
1905-1910	Greenwich ...	-5·7	-0·7	+ 2	-19
	Kew	-5·9	-1·0	0	-36
	Stonyhurst ...	-6·7	-0·9	+ 8	-23
	Falmouth ...	-5·4	-1·4	+11	-24
	Valencia ...	-5·2	-1·2	+ 9	-24
	Mean	-5·8	-1·0	+ 6	-25

Table I. gives mean secular change data from five-year periods ranging from 1860 at Kew, and from 1895 at the other stations, except Valencia (County Kerry), where they really range from 1901. The data prior to 1890 are

from absolute observations. A correction had been applied which was intended to eliminate the diurnal inequality of declination. This correction was really derived from the mean diurnal inequality of the nine years 1858, 1859, 1860, 1861, 1862, 1870, 1871, 1872, 1888. The mean sunspot frequency of these years, 82·2, is, however, considerably above the average, and consequently the diurnal inequality must in the average year have been over-corrected. Still with a five-year interval the consequences of this defect would not be serious.

In the sequence of events at Kew we see several noteworthy changes. Between 1860 and 1880 westerly declination diminished at a very uniform rate, averaging 8′·3 per annum. If in 1880 one had forecasted on this basis what the declination would be in 1900 one would have obtained 16°5′·3, whereas the value proved to be 16°52′·7; thus the estimate would have been 47′·4 in error. If again one had been obliged to make a forecast of declination at Kew about 1900, the great falling off during recent years in the rate of secular change must have inspired a doubt as to whether the easterly movement of the needle was not destined to die away altogether in the course of a few years, and be succeeded by a reverse movement to the west. Several years had to elapse before it became clear that the slackening in the secular change was only temporary. These cases will serve to illustrate a danger attending the construction of charts, which naturally depend in large measure on data derived from years considerably anterior to the epoch to which they profess to apply.

It will be noted that the differences shown by Table I. between the secular changes of *D* at the different British observatories are small. The agreement between the different stations is much less apparent in the case of *I*. How far these differences are real, and how far they arise from instrumental defects is open to doubt. Judging

by the Kew data, the secular change of I was very uniform from 1860 to 1875 and then declined until 1895. Since 1900 it has diminished again, especially during the last few years.

The secular changes of H recorded at the different British observatories are very similar for the epochs 1895–1900 and 1900–1905, but since 1905 there are conspicuous differences. These differences, moreover, appear to be real and are connected with a very interesting phenomenon. Until about ten years ago H was rising fairly steadily at all European observatories. A decline then appeared in the rate of change in Russia, and in the course of a few years the rise died out entirely at Pavlovsk (near St. Petersburg) and was succeeded by a fall. The phenomenon seen at Pavlovsk spread rapidly to the west, appearing successively at Potsdam and the observatories of the Netherlands, Belgium and France, and then at Greenwich and Kew. In 1908–9, H fell in the east of England, while still rising in the west and Ireland. Supposing the westward drift of the line of no secular variation to continue, one would have anticipated for 1909–10 an increased rate of fall at Greenwich, Kew and Stonyhurst, and a zero or diminished rate of rise at Falmouth and Valencia. At Stonyhurst, where the fall increased, and at Falmouth, where the value was stationary, this anticipation would have been realised. But Valencia showed an increased rise 15γ, while Greenwich and Kew also showed rises, the latter indeed insignificant, 1γ, but the former 6γ. One would thus infer a check in the westward drift of the line of no secular variation so far as Great Britain is concerned. Whether this is purely temporary and peculiar to Great Britain, or whether it betokens a return to the conditions prevailing in Europe prior to 1900, time alone will show.

The differences between the secular changes obtained for V at neighbouring stations such as Greenwich and Kew

are somewhat suggestive of instrumental errors. According to the Kew figures, V increased in the decade 1880–1890, while decreasing prior to 1880 and again subsequent to 1891. The apparent rise between 1880 and 1891 was about 130γ, which seems too large to ascribe to instrumental defects.

TABLE II.—*Secular Change.*

Year.	Falmouth.	Kew.						
	D.	*D.*	*I.*	*H.*	*W.*	*N.*	*V.*	*T.*
	′	′	′	γ	γ	γ	γ	γ
1890–1	—	−8·7	−1·0	+24	−36	+37	+18	+30
1891–2	−5·2	−5·2	−1·2	+11	−23	+19	−22	−12
1892–3	−6·6	−7·9	−3·0	+34	−30	+45	−20	−11
1893–4	−5·7	−5·8	−1·4	+13	−25	+21	−21	−13
1894–5	−6·3	−6·2	−2·2	+27	−24	+36	−13	−4
1895–6	−7·0	−6·0	−2·7	+31	−21	+39	−21	−8
1896–7	−5·3	−4·4	−3·1	+33	−13	+40	−31	−17
1897–8	−4·7	−5·0	−2·0	+22	−19	+27	−21	−9
1898–9	−4·8	−4·3	−2·9	+29	−13	+35	−33	−21
1899–1900	−3·6	−4·4	−2·9	+35	−13	+40	−21	−5
1900–1	−3·6	−3·8	−2·3	+23	−12	+28	−27	−17
1901–2	−4·0	−4·1	−1·5	+24	−15	+29	+5	+13
1902–3	−3·2	−4·3	−1·5	+13	−18	+20	−25	−16
1903–4	−6·3	−2·6	−1·4	+16	−9	+19	−10	−4
1904–5	−3·6	−5·0	−1·3	+6	−24	+13	−32	−28
1905–6	−3·1	−4·4	−1·6	+10	−20	+17	−33	−26
1906–7	−4·9	−5·4	−0·6	−3	−29	+5	−28	−27
1907–8	−5·7	−6·2	−0·7	−2	−32	+7	−30	−28
1908–9	−6·3	−6·1	−1·2	−7	−33	+2	−59	−56
1909–10...	−6·8	−7·6	−1·0	+1	−39	+12	−31	−30
1890–1895	−6·0	−6·8	−1·8	+22	−28	+32	−12	−2
1895–1900	−5·1	−4·8	−2·7	+30	−16	+36	−25	−12
1900–1905	−4·1	−4·0	−1·6	+16	−16	+22	−18	−10
1905–1910	−5·4	−5·9	−1·0	0	−31	+9	−36	−33

Table II. gives the apparent annual secular change at Kew since 1890, and for comparison, the corresponding Falmouth changes of declination since 1891. It includes Kew data for the west and north components and for the total force as well as for the more usual elements.

Declination data from Kew and Falmouth are much more harmonious than those for the other elements. In

the nineteen common years included, the mean difference between the apparent annual changes in *D* at the two stations taken irrespective of sign is only 0′·78, and this becomes 0′·62 if we omit 1903–4. In this year the Falmouth estimate is considerably in excess of the estimates at Greenwich, Valencia, and Stonyhurst, where the respective values were 4′·1, 3′·5, and 3′·7; on the other hand, the Kew estimate is apparently low.

Taking the ten last years included in the table, the average difference irrespective of sign between the Kew values and those at the other stations was 0′·89 for Greenwich, 1′·28 for Stonyhurst, 0′·98 for Falmouth, and 0′·76 for Valencia (nine years). We should naturally have expected these differences to increase with the distance between the stations, but this cannot be said to be the case. If we take a mean secular change from the five stations combined, we obtain the following values for the last nine years in the table in their chronological order:

−4′·0, −3′·8, −4′·0, −4′·6, −4′·6, −4′·7, −6′·4, −6′·1, −7′·0.

The progression here is decidedly smoother than for any one of the stations. It must thus, I think, be concluded either that the yearly values of secular change at British stations are affected even in the case of the declination by uncertainties of the order of at least ten per cent., or else the secular change at any one station progresses in a somewhat spasmodic way, there being superposed on the general drift minor irregularities, so local in their incidence as to differ markedly at stations so contiguous as Kew and Greenwich.

The theory has been advanced recently by Dr. E. Leyst[1] of Moscow, that at least at some stations secular change of declination is larger at sunspot maximum than at sunspot minimum. According to Leyst's figures secular changes

[1] *Bull. de la Société Impér. des Naturalistes de Moscou*, 1909, pp. 160–162.

at these epochs are at Greenwich in the ratio of 1·95 to 1. Conclusions so remarkable call for a strict scrutiny. Sunspot maximum and minimum are independent of geographical position, while the secular change in D varies with the geographical co-ordinates. At a given period the needle will be moving to the west at one station, to the east at another, and be as nearly as possible stationary at a third. Twenty years later the place where the needle was stationary may show a considerable secular change. We are thus led to suspect that if the secular change from a particular station has shown the phenomenon which Leyst describes, it is an accident. The phenomenon is certain to present itself at some stations when data are derived from a limited number of eleven-year periods. For instance, if we confined ourselves to the last twenty years at Kew, and compared the two three-year periods, 1892–5 and 1905–8, representing many sunspots, with the six intermediate years, 1897–1903, representing few sunspots, we should find the following results:—

Six years of many sunspots.		Six years of few sunspots.	
Mean sunspot frequency.	Mean secular change.	Mean sunspot frequency.	Mean secular change.
67·2	$-6'{\cdot}0$	13·6	$-4'{\cdot}3$

This apparent confirmation of Leyst's theory, however, arises simply from the fact that a conspicuous minimum in the rate of secular change *happened* to come in the selected period of few sunspots. If we take the long period 1860–1910, the phenomenon is no longer clearly seen. Taking the secular changes for three successive years at each period of sunspot maximum and minimum, we obtain the data in the following table:

TABLE III.—*Kew Secular Change at Times of Sunspot Maximum and Minimum.*

Sunspot maximum.			Sunspot minimum.		
Period.	Mean frequency.	Mean change.	Period.	Mean frequency.	Mean change.
		′			′
1860–63	68·7	−7·90	1865–68	19·2	−8·50
1869–72	112·7	−7·87	1876–79	8·1	−8·57
1881–84	60·8	−6·13	1887–90	7·7	−5·47
1892–95	77·1	−6·63	1899–1902	6·9	−4·10
1905–08	57·3	−5·33			
Means	75·3	−6·77	Means	10·5	−6·66

The difference between the mean sunspot frequencies for the groups of sunspot maximum and minimum years in Table III. is greater than it was for the contrasted groups taken from the last twenty years, but the difference between the two mean secular changes of D in the table is practically nil.

While the secular change figures for Kew in Table II. are distinctly less smooth for the other elements than for D, they do not present any very conspicuous irregularities. Every year has seen a decrease in W, the total fall since 1890 representing above 8% of the original value. Numerically regarded, the increase in N during the twenty years has exceeded the fall in W, but the percentage rise is only a little above 2·8. The rate of rise in N began to slacken at the same time as the rise in H, but the former element continued to rise after 1906, though at a much reduced rate.

With the exception of the one year 1901–2, V and T have fallen continuously since 1891, and of late years at an accelerated rate. The total falls since 1891 represent, however, only about 1·1 per cent. of the original value of V and 0·6 per cent. of the original value of T. Considering the smallness of the change in T, the fact that only one year has shown an apparent increase is a little remarkable.

Fig. 4 supplies a graphical representation of the changes in D, I and H since 1860 at Kew.

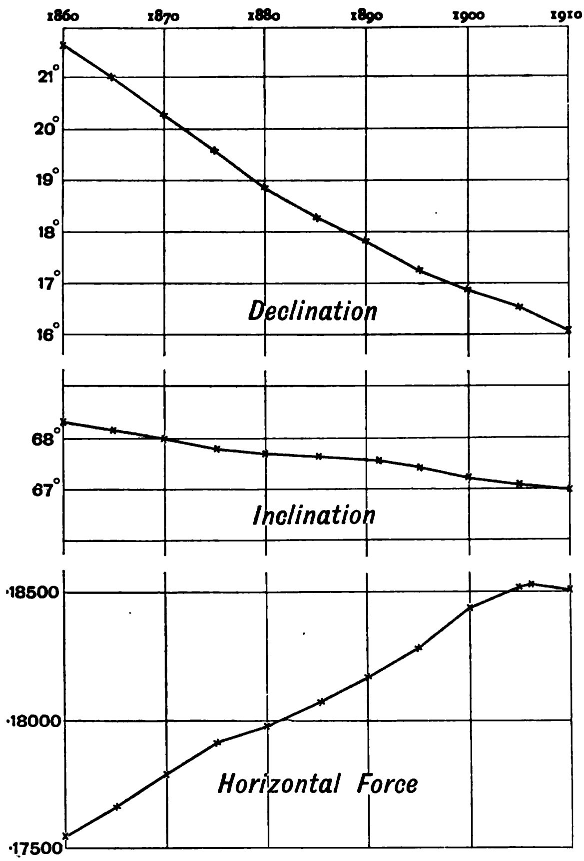


FIG. 4.—SECULAR CHANGE AT KEW.

An instructive way of picturing the secular change is to regard it as due to a disturbing force. If ΔN, ΔE and ΔV represent the increments of N, E (easterly component) and V due to secular change in the course of a year, then the force of which these are the three rectangular co-ordinates may be regarded as producing the change.

If $\Delta\rho$ be the component of this force in the horizontal

plane, and ϕ be the inclination of the vector $\Delta\rho$ to geographical north, measured from north to east,

$$\Delta\rho = \sqrt{\Delta N^2 + \Delta E^2}, \ \tan\phi = \Delta E / \Delta N.$$

If further

$$\Delta R = \sqrt{\Delta\rho^2 + \Delta V^2} \equiv \sqrt{\Delta N^2 + \Delta E^2 + \Delta V^2},$$

and

$$\tan\theta = \Delta\rho \ \Delta V,$$

then ΔR represents the resultant disturbing force—of which $\Delta\rho$ and ΔV are respectively the horizontal and vertical components—and θ is its inclination to the vertical. Measuring θ from the zenith we obtain the data given in Table IV.

TABLE IV.—*Coordinates of Secular Change Force at Kew.*

Epoch.	1860–80.	1880–90.	1890–1900.	1860–1900.	1900–05.	1905–10.
ϕ	47°	34°	33°	40°	36°	74°
θ	71°	112°	66°	79°	56°	41°
$\Delta\rho$	47γ	41γ	40γ	43γ	27γ	32γ
ΔR	49γ	44γ	44γ	44γ	32γ	48γ

Between 1880 and 1890 the vertical force increased, so that the disturbing force was directed below the horizon. The transition of course from 112°, the mean value obtained for θ for that decade, to 66° the corresponding mean for the next decade was gradual.

The angle ϕ showed no great alteration from 1860 to 1900, but since then it has roughly doubled.

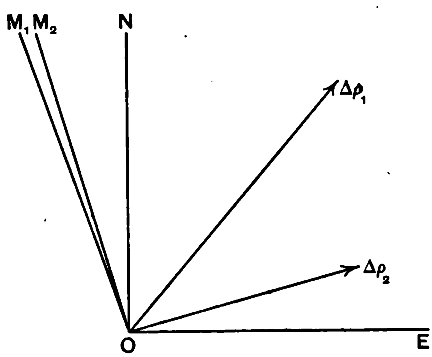


FIG. 5.—KEW SECULAR CHANGE FORCE.

In the accompanying Fig. 5, ON, OE are horizontal axes in and perpendicular to the geographical meridian. OM_1 and OM_2 represent the mean positions of the magnetic

meridian for 1860-1900 and 1905-1910 respectively. $\Delta\rho_1$ and $\Delta\rho_2$ represent in magnitude and direction the horizontal components of the disturbing force for these two periods. As long as $\Delta\rho$ and OM were inclined at less than 90°, the horizontal force tended to increase, but of late years the inclination has if anything slightly exceeded 90°.

The comparative uniformity in the values of ΔR for the different periods is somewhat remarkable. This does not, however, imply that its value may not have fluctuated considerably from year to year.

CHAPTER III

NON-CYCLIC CHANGE

NON-CYCLIC change is a phenomenon which will be more readily understood if we consider a simpler element than Terrestrial Magnetism. Let us take the diurnal change of temperature in England in April. The most conspicuous phenomenon is the rise from a minimum in the early morning to a maximum in the afternoon, and the subsequent fall to the next day's minimum. But superposed on this is a seasonal change. Every day is not warmer than the preceding, but the general tendency is towards a rise of temperature. Thus when we calculate the mean diurnal variation of temperature for April in an average year, by assigning to each hour of the day the mean for that hour derived from the whole thirty days, we find that the second midnight of the representative day is slightly warmer than the first midnight. The excess obviously represents the one-thirtieth part of the rise in temperature during the month. In the case of temperature we have a rise in spring and a corresponding fall in autumn, so that when we take the average day of the average year the difference between the first and second midnights disappears.

Thus in the case of temperature and other meteorological elements—assuming no real climatic change in progress, such as approach to a glacial epoch—we have an aperiodic or non-cyclic change in the diurnal variation found for individual months, but not in that found for the whole year. Passing now to Terrestrial Magnetism, we have normally, even in the mean diurnal variation for the whole

year, a phenomenon parallel to that seen in the diurnal variation of temperature for individual months. If we compare the values of the magnetic elements at Kew in 1891 and 1910 we find

	D.	*I.*	*H*	*V.*
	° ′	° ′		
1910	16 3·2	66 58·7	0·18503	0·43546
1891	17 41·9	67 33·2	0·18193	0·44034
Change in 19 years =	−1 38·7	−0 34·5	+0·00310	−0·00438
Change per year =	−0 5·19	−0 1·82	+16·3 γ	−25·7 γ

Thus in the average day of the above nineteen years we had the following non-cyclic changes :—

in D, $-0'{\cdot}014$; in I, $-0'{\cdot}0050$; in H, $+0{\cdot}045\,\gamma$; in V, $-0{\cdot}070\,\gamma$.

In addition to this natural change most magnetic curves show a non-cyclic change of instrumental origin. Take for example the H curve. The H magnet is twisted into a position at right angles to the magnetic meridian, where the torsion couple τ balances the magnetic couple mH, due to the action of the horizontal force H on the magnet, supposed of moment m. Obviously the position of the magnet will vary if either τ or mH varies. Usually m gradually diminishes, so that if τ and H remain constant the torsion couple prevails. The extent of the movement depends on the decline of mH; whether this is due to fall in m or fall in H is immaterial. Thus the drift in the magnet's position, and consequently in the length of the curve ordinate, simulates a fall in the magnetic force.

Change may not be confined to the magnetic moment. The suspension, for instance, may deteriorate and the torsional couple diminish. Such a change would simulate a rise in magnetic force.

At Kew in the H magnetograph there is a slow drift in the direction answering to a decline in the magnetic moment. The average change due to this cause has been the same as if H diminished by about 20γ per annum, or

roughly $0{\cdot}05\gamma$ in the twenty-four hours. As it so happens this is nearly equal and opposite to the mean secular change in H between 1890 and 1910.

The vertical force curves are affected by similar non-cyclic changes from instrumental sources. The declination curves have the advantage of being practically free from this, the only certain source of non-cyclic change in their case being the secular change.

Taking then an average day at Kew, the non-cyclic changes which we should expect to find in the course of the twenty-four hours are a fall of about $0'{\cdot}014$ in D, a change not exceeding $0{\cdot}02\gamma$ in H, and a somewhat similar change in V. It might thus appear at first sight that for accuracy to 1γ or $0{\cdot}5\gamma$ non-cyclic changes need hardly be taken into account in magnetographs of the Kew pattern. This expectation, unfortunately, is far from being realised in circumstances that actually arise. The difficulty of dealing with highly disturbed magnetic curves was early recognised. A single highly disturbed reading may destroy the smoothness of the diurnal variation derived from an entire month. The most obvious way of meeting such difficulties was to omit disturbed days entirely, and a natural development of this idea was to derive diurnal inequalities from a limited number of days selected as being "quiet" or free from apparent irregular movements. This plan had the further recommendation of greatly diminishing the labour necessary to obtain diurnal inequalities. It was largely this consideration that led the Kew Committee in 1889 to come to an understanding with Greenwich, in virtue of which five days a month were selected by the Astronomer Royal as conspicuously quiet, and since that date only five days a month have been tabulated at Kew or at Falmouth.

The last midnight of one day being the first midnight of the next, when all days are tabulated it is most usual to record the values of a magnetic element at hours 1, 2, 3 up to 24. Quiet days, however, are largely isolated, so the

usual practice would omit information as to one of the two midnights. It not being obvious which to omit, the practice was fortunately adopted at Kew of retaining both. This led in 1895 to the discovery of the special non-cyclic changes characteristic of quiet days. When discussing the diurnal inequalities obtained for H from the quiet days of the years 1890 to 1894, my suspicions were roused by the fact that the value for the second midnight exceeded that for the first midnight in a majority of cases far too large to ascribe to accident. A minute investigation, taking Falmouth data into account as well as Kew data, showed that the fact was a natural phenomenon, and not of instrumental origin as was at first feared.

Table V. gives the observed non-cyclic changes for the average quiet day of the year stated, for D, H, I and V at Kew, and for D and H at Falmouth.

TABLE V.—*Mean Daily non-cyclic Change on Quiet Days.*

Year.	*D.*		*H.*		*I.*	*V.*
	Kew.	Falmouth.	Kew.	Falmouth.	Kew.	Kew.
	′	′	γ	γ	′	γ
1890	−0·36	—	+2·3	—	−0·10	+1·5
1891	+0·29	+0·075	+2·3	+2·6	−0·18	−1·25
1892	+0·14	−0·08	+5·3	+4·4	−0·41	−2·0
1893	+0·26	+0·27	+4·0	+4·25	−0·35	−2·6
1894	+0·15	+0·18	+3·3	+3·0	−0·175	+1·25
1895	−0·05	+0 07	+4·4	+4·7	−0·33	−1·5
1896	−0·01	+0·04	+3·8	+3·2	−0·27	−1·4
1897	−0·04	+0·025	+3·7	+3·9	−0·275	−0·7
1898	+0·025	−0·02	+2·8	+2·6	−0·225	−0·7
1899	+0·05	−0·01	+3·2	+2·4	−0·23	−1·2
1900	+0·025	+0·01	+1·6	+1·75	−0·13	−0·5
1901	−0·09	+0·02	+2·0	+1·5		
1902	+0·11	+0·03	+2·3	+1·5		
1903	+0·24	+0·41	+2·9	+2·7		
1904	+0·39	+0·10	+3·4	+3·4		
1905	+0·225	+0·025	+2·3	+1·8		
1906	−0·35	−0·01	+2·75	+2·5		
1907	+0·16	+0·12	+3·0	+2·2		
1908	−0·01	0·00	+2·9	+2·0		
1909	−0·225	+0·06	+2·2	+2·4		
Means	+0·047	+0·069	+3·03	+2·78	−0·245	−0·84

The sign of the mean non-cyclic change in *D* differs in different years, and the parallelism between the results at the two observatories is not close. This suggests considerable dependence on local peculiarities. In the case of *H* it is otherwise. The non-cyclic change is positive in every year, and a fairly close parallelism can be seen between Kew and Falmouth. The non-cylic change in *H* on the average quiet day at Kew is some ten per cent. of the range of the regular diurnal inequality. It is even more important relatively in the case of *I*, where it attains to about fifteen per cent. of the inequality range. The average non-cyclic change in *V*, shown by Table V., is a decrease, but the effect is much less than in *H*.

Table VI. gives the observed mean values of the non-cyclic changes on quiet days at different seasons of the year. Winter includes the four months November to February, summer the four months May to August, and equinox the remaining four months. The Kew data are from the twenty years 1890 to 1909, the Falmouth from the nineteen years 1891 to 1909.

TABLE VI.—*Mean non-cyclic Changes on Quiet Days.*

Season.	*D*.		*H* (unit 1γ).		*I*.	(*V* unit 1γ).
	Kew.	Falmouth.	Kew.	Falmouth.	Kew.	Kew.
	′	′			′	
Winter .	+0·122	+0·046	+3·01	+2·68	−0·252	−0·68
Equinox .	+0·023	+0·149	+3·04	+2·79	−0·254	−0·46
Summer .	−0·005	+0·012	+3·04	+2·86	−0·230	−1·39

There is little if any indication of seasonal variation in the figures for *H* and *I*. In the case of *D*, the fact that the summer values are specially small both at Kew and Falmouth creates at least a presumption that the phenomenon is a real one.

Table VII., which is based on the same data as Table VI., shows the percentage of months having the non-cyclic change on the average quiet day respectively positive,

zero and negative. The results for each month, it must be remembered, depend on only five days, so that accident naturally plays some part in the result.

TABLE VII.—*Signs of non-cyclic Changes on Quiet Days in Individual Months.*

Station.	*D.*			*H.*			*I.*			*V.*		
	+	0	−	+	0	−	+	0	−	+	0	−
Kew	48	11	41	86	7	7	10	12	78	36	7	57
Falmouth	49	14	37	81	9	10	—	—	—	—	—	—

If we take the 228 months of the nineteen years, 1891 to 1909, for which synchronous results exist for Kew and Falmouth, and compare the signs of the non-cyclic changes for the same months at the two stations, we obtain the statistics embodied in Table VIII.

TABLE VIII.—*Degree of Accordance in Sign of non-cyclic Effect at Kew and Falmouth.*

Element.	Months agreeing in sign.	Months when effect nil at one of the stations.	Months differing in sign.
Declination	132	52	44
Horizontal force	183	35	10

Even in the case of *D* there is a large preponderance of cases in which the signs of the non-cyclic changes at the two stations agree. The stations compared, it will be remembered, are some 200 miles apart.

If all days behaved like the average quiet day of the period dealt with in Table VI., we should have the following annual changes at Kew: in D, $+17'\cdot2$; in H, $+1107\,\gamma$; in I, $-89'\cdot5$; and in V, $-307\,\gamma$. At this rate, H would have been twice as large in 1907 as it was in 1890, while I in the same time would have fallen 25°. Thus, trifling as the non-cyclic effect may appear at first sight, it represents a very potent influence.

In accordance with an international understanding, it has been the practice at many observatories since 1906 to divide all the days of the year into three classes, "0," "1" and "2," according to the degree of disturbance, "0" representing the least disturbed days. Taking an average from the three years 1906 to 1908, there were 142 days, or above 38 per cent., classed as "0" at Greenwich, and an identical number were similarly classed at Kew. The majority of these days are similar in quietness to the five days a month selected by the Astronomer Royal. Thus the sum of the non-cyclic changes taking place on quiet days in *H* and *I* must be enormous compared to the secular change actually recorded.

It follows that there must be a tendency in the opposite direction on the average day that is not quiet. This aspect of the case occurred to me when first describing the non-cyclic effect on quiet days, and I hazarded the remark that it was not unlikely to prove only another phase of a phenomenon observed long ago by General Sabine at Kew and by Dr. Humphry Lloyd at Dublin. The former observed that a large majority of magnetic disturbances led to a fall in *H*, while a distinct majority produced a rise in *V*. A recent investigation has shown that the non-cyclic phenomena on disturbed days at Kew are of a somewhat complicated character. A selection was made from the eleven years 1890–1900 of the days of most conspicuous disturbance in the *D* curves, 209 in all. An analysis of the 209 days gave the results in Table IX.

TABLE IX.—*Non-cyclic Changes at Kew on highly Disturbed Days.*

	D.	*I.*	*H.*	*V.*
Mean non-cyclic change...	$+\ 0'{\cdot}33$	$+0'{\cdot}95$	$-\ 13{\cdot}2\,\gamma$	$+\ 2{\cdot}7\,\gamma$
Days when sign plus ...	109	—	81	113
,, ,, value zero ..	0	—	0	3
,, ,, sign minus ...	100	—	128	93

The non-cyclic change in Table IX. in I, H and V is thus opposite in sign to that on the average selected quiet day, and is numerically from three to four times as large. There is thus a compensation. In D, however, the non-cyclic change in Table IX. has the same sign as in the average quiet day, and the compensating effect—representing a movement to the east—is supplied by the days of intermediate type. The majority in the number of days giving a plus non-cyclic change in D is not large, either for the quiet class or the highly disturbed. In the case of H and I, while by no means all quiet days gave the dominant sign, the majority doing so was large. Amongst the highly disturbed days the majorities giving the dominant sign are considerably smaller. There seems more than one reason for this. On a highly disturbed day short period oscillations of force are frequent, and there may be a crest at one midnight and a hollow at the other.

There is thus a considerable quasi-accidental factor in the non-cyclic change in individual disturbed days. But, besides this, there is a difference between different days, depending on how long the disturbance has been in progress and what stage it has reached. Of the 209 selected highly disturbed days at Kew the majority occurred in groups of two, three, four or more days, *i.e.* the highly disturbed character in the majority of cases lasted during two or more consecutive days. It was found that the nature of the non-cyclic change depended largely on whether the day was one of isolated disturbance or formed one of a group of disturbed days, and in the latter event on what position it occupied in the group. When the days were analysed according as they were days of isolated disturbance, or came first, second or third in a group of disturbed days, very different results were obtained from the different classes, as will appear on consulting Table X.

TABLE X.—*Mean non-cyclic Changes at Kew on Disturbed Days.* (*Unit* 1γ.)

	Isolated days.	1st days.	2nd days.	3rd days.
Number of days.	64.	61.	61.	15.
D	+ 5·1	−24·1	+22·3	+ 8·6
H	−24·4	−40·4	+18·3	+13·8
V	+ 2·9	−21·3	+27·1	+ 6·2

A change of 1′ in *D* represents at Kew a change of 5·3γ in the component of force perpendicular to the magnetic meridian, and the *D* changes in Table X. are represented in terms of the equivalent force.

Table X. shows that when a large disturbance extends over two or more days there is a marked tendency to an oscillation, *D*, *H* and *V* all falling during the first day and then rising. In each instance the signs shown in the table, while representing the mean effect, were exhibited only by a majority of the days concerned.

The percentages which the majority formed of the whole number of days were as follows:

Element.	Isolated days.	1st days.	2nd days.	3rd days.
D...............	58	69	69	53
H...............	78	80	67	73
V...............	52	62	70	67

For instance, there were 61 "first days" of disturbance, and of these 42, or 69 per cent., showed a fall in *D*; 49, or 80 per cent., a fall in *H*; and 38, or 62 per cent., a fall in *V*.

On a highly disturbed day the non-cyclic change during the twenty-four hours represents in general, not a steady drift in one direction, but an excess in the total amplitude of numerous changes in one direction over the changes in the opposite direction.

The true nature of the physical relationship between non-cyclic changes on quiet and on disturbed days is still a matter of speculation. At the end of large magnetic storms, in a majority of instances, *H* is lower and *I* higher

than before the storm began. The disturbance has thus apparently produced some sub-permanent change in the earth's magnetism, which does not immediately disappear, and the non-cyclic change on quiet days may be analogous to the "creep" observed in metal recovering from overstrain. On the other hand, the non-cyclic changes on quiet days may be the primary phenomenon, and the magnetic storm may act similarly to a shock applied to a permanent magnet.

CHAPTER IV

DIURNAL INEQUALITY

When mean hourly values of a magnetic element are derived from a very large number of days, we obtain a smoothly progressing variation representing the regular diurnal change on the average day. If the days are of a particular class, or if the secular change be very large, the hourly values thus obtained contain a sensible non-cyclic or aperiodic element, which requires to be eliminated before we obtain figures which are periodic in the twenty-four hours. If N denote the excess at the second midnight of the representative day as compared to the first midnight, and n denote any hour of the day reckoned from 0 (first midnight) to 24, the correction

$$N(12-n)/24$$

obviously brings the values for the two midnights into agreement, and eliminates the non-cyclic element completely, provided we may assume that N comes in at a uniform rate throughout the twenty-four hours.

The hypothesis that N does come in at a uniform rate is usually made tacitly. Its proof or disproof presents difficulties. It seems the only workable hypothesis when information as to non-cyclic changes is confined to the twenty-four hours ending with midnight. After eliminating the non-cyclic change we may drop the first midnight value, leaving values for the hours 1 to 24. Taking in succession the difference of each hourly value from the

arithmetic mean of the twenty-four, we obtain what is known as the *diurnal inequality.*

The smooth progression observed in hourly means from a very large number of days is seen but in a very few, if any, of the individual days. On the great majority there are irregular variations, sometimes much larger than the range of the regular diurnal inequality. The variations on any individual day are usually regarded as resulting from the superposition of a regular diurnal variation and magnetic disturbances. This may be true in a sense, only, as will be seen later, the character of the diurnal inequality is not independent of the presence of the disturbance. If we divide all days into three groups, comprising respectively the very quiet, the very disturbed, and the days intermediate between those of the two first groups, we get in each case a smooth diurnal inequality, provided a sufficient number of days are included. But the three inequalities are different.

There seems originally to have been a disposition to assume that the regular diurnal inequality was something independent of disturbance, and consequently that so long as a smooth inequality was obtained, it did not matter whether one included all days of the month or only a selection. This belief is now known to require modification, but it does not follow that the use of selected quiet days should necessarily be given up. Owing to the exigencies of time, the choice at some stations may be between inequalities from quiet days and no inequalities at all. Again, at other stations it may be possible to derive inequalities from quiet days as well as from all days, and thus obtain information that is not forthcoming from either species separately. It is clearly desirable, however, if use be made of quiet days, that the selection made at different stations should be the same, or as nearly so as possible. Hitherto use has been made at Kew and Falmouth of five quiet days a month selected by the

Astronomer Royal. But the observatories of the U.S. Coast and Geodetic Survey base their inequalities on ten quiet days a month. At Pavlovsk, on the other hand, the monthly number of quiet days varies and is often less than five.

At some stations inequalities are derived from all days of the month for which records are complete. Other stations exclude the days of very large disturbance, even when there is no loss of record. Greenwich, Parc St. Maur and Pavlovsk publish two sets of diurnal inequalities, one based on quiet days only. Thus the diurnal inequalities published by different observatories are not strictly comparable. Further, while most magneticians will readily allow the advantage of having data that are strictly comparable, there are many difficulties in the way of securing this end. At one station, if we omit the five most disturbed days of a month, we shall avoid all the disturbances of moment; but at a second station, even the quietest day of the month would be considered disturbed at the first station.

A priori there is much to be said for deriving inequalities at all stations from one and the same choice of days, meaning by "day" a twenty-four-hour period commencing at Greenwich midnight. The results would be at least contemporaneous, and would represent one and the same condition of the earth's magnetism. Such an object can hardly be secured except by international agreement. Of late years a selection of five quiet days a month has been made at de Bilt, near Utrecht, under the auspices of the International Committee of Terrestrial Magnetism, based on returns from observatories all over the globe. These days commence at Greenwich midnight, and may fairly be regarded as representing the quietest state of matters for the earth as a whole. It is intended in future years to adopt these as the quiet days at Kew, and if any considerable number of observatories follow a like course, we

may hope to have fairly corresponding data for days of one class.

It has been suggested by the writer that if the days of each month were subdivided under international auspices into three classes, made up of the five quietest, the five most disturbed, and the intermediate days, and if three sets of inequalities were thence derived, more information would be forthcoming than from two inequalities, one derived from the quiet days, the other from all days (or all but very highly disturbed days) including the five quiet days. This, however, is only a future possibility. In this chapter attention will be confined to results derived from the five quiet days a month selected by the Astronomer Royal.

The amplitude of the diurnal inequality varies from year to year, fluctuating, as we shall see in a later chapter, with sunspot frequency. Thus, when comparing different stations, it is desirable to obtain data from a common period of years, preferably an entire eleven-year period.

The diurnal inequality varies greatly with the season of the year. In temperate latitudes the range is usually much larger in summer than in winter. Even the type of the inequality varies with the season, especially towards the equator, where the winter and summer inequalities present widely different features.

When the diurnal inequalities for any three magnetic elements are known, those for the others can be calculated. The elements of which diurnal inequalities are most frequently given are *D*, *I*, *H* and *V*, but inequalities of *T*, and also of late years of *N* and *W*, are by no means uncommon.

Table XI. gives the diurnal inequalities at Kew in June and December for *D*, *I*, *H* and *T*, derived from the quiet days of the eleven-year period, 1890–1900, and Table XII. does the same for *N*, *W* and *V*. The non-cyclic

element has been eliminated in the way explained on page 33.

The results are shown graphically in Figs. 6 and 7, the ordinate scale being the same for the four force elements.

Well marked maxima and minima values in the tables, whether primary or secondary, are in heavy type.

TABLE XI.—*Diurnal Inequality at Kew.* (*Quiet Days* 1890–1900.)

Hour.	*D.*		*I.*		*H* (unit 0·1γ).		*T* (unit 0·1γ).	
	June.	Dec.	June.	Dec.	June.	Dec.	June.	Dec.
	′	′	′	′				
1	-0·74	-0·56	-0·29	+0·08	+44	-9	+26	0
2	-0·98	-0·30	-0·24	+0·06	+33	-6	+14	**0**
3	-1·23	-0·23	-0·21	-0·04	+31	+6	**+14**	+2
4	-2·00	**-0·23**	-0·17	-0·15	+28	+23	+16	+11
5	-3·41	-0·26	-0·04	-0·22	+14	+34	**+19**	**+16**
6	-4·60	-0·46	+0·26	-0·27	-36	+42	-9	+15
7	**-5·02**	-0·63	+0·68	**-0·30**	-98	**+44**	-42	+12
8	-4·79	-0·77	+1·03	-0·20	-162	+29	-91	+3
9	-3·63	**-0·80**	**+1·27**	-0·07	-213	+2	-150	-18
10	-1·23	+0·01	+1·26	+0·16	**-233**	-38	-200	-45
11	+1·63	+0·98	+0·95	**+0·33**	-205	**-62**	**-225**	**-53**
Noon	+4·42	+1·83	+0·51	+0·28	-133	-52	-190	-49
1	**+5·60**	**+2·25**	+0·21	+0·17	-73	-25	-130	-25
2	+5·50	+1·79	-0·09	+0·19	-3	-19	-45	-4
3	+4·49	+1·34	-0·27	+0·15	+47	-9	+21	+11
4	+3·20	+0·74	-0·34	+0·06	+71	+1	+77	+23
5	+1·83	+0·27	-0·50	-0·03	+102	+6	+121	+24
6	+1·00	-0·01	-0·65	-0·11	+136	+20	+144	**+26**
7	+0·38	-0·33	**-0·75**	**-0·14**	**+153**	**+22**	**+158**	+22
8	+0·17	-0·68	-0·68	-0·08	+137	+13	+145	+14
9	+0·06	-0·97	-0·62	-0·03	+122	+3	+120	+7
10	+0·14	**-1·09**	-0·52	0·00	+96	-3	+92	+4
11	-0·28	-0·99	-0·45	+0·03	+76	0	+65	+5
12	-0·55	-0·90	-0·36	**+0·09**	+61	**-13**	+48	0

The first thing that strikes one when comparing the June and December inequalities in Tables XI. and XII. is the enormous difference in the ranges. December is the month in which the range is least at Kew in all the elements, and the minimum is a marked one. There is no marked maximum, there being no great difference in the range from May to August; still the range in June is

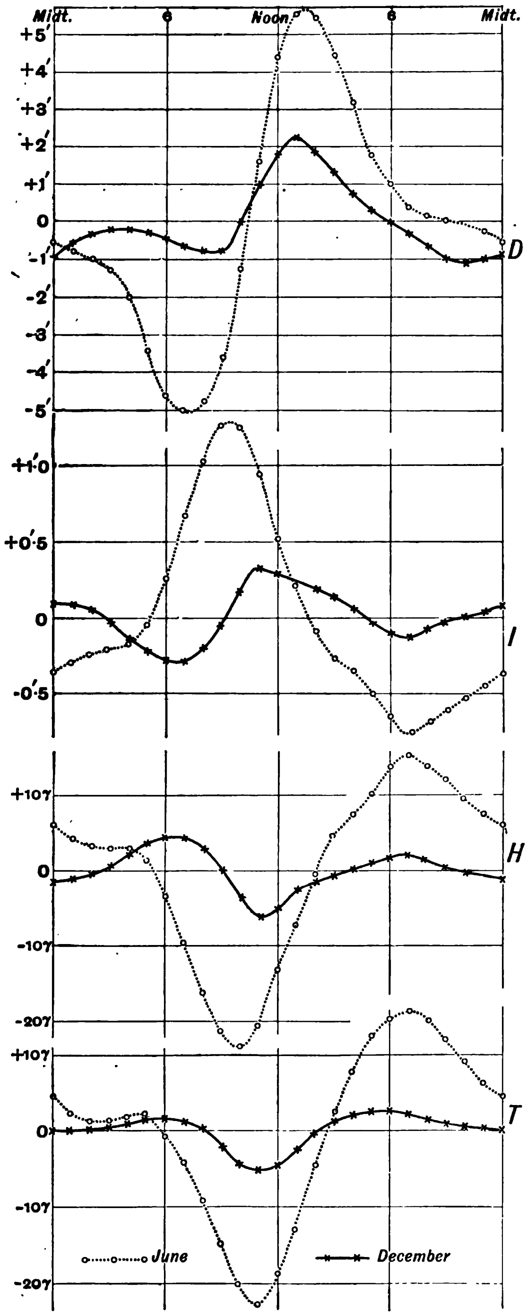


FIG. 6.—KEW QUIET DAY DIURNAL INEQUALITY.

largely in excess of that in any month from October to March.

A not uncommon use made of diurnal inequalities is in applying a correction to an observation made at one particular hour of the day, to reduce it to the mean value for the twenty-four hours. It will be already sufficiently clear from Tables XI. and XII. that a mean diurnal inequality derived from all months of the year is not at all suitable for purposes of this kind. The best plan is to have recourse to the magnetic curve for the actual day of observation, but if that is impossible, use should be made of the diurnal inequality for the particular month.

More minute examination of Tables XI. and XII. will

show that corresponding maxima and minima in June and December often occur at different hours, and that the equivalent of what is a principal maximum in one month may be only a secondary maximum in the other. As a general rule, if a maximum or minimum occurs near noon in the mean diurnal inequality for the year, its hour of occurrence is less variable from month to month than if it

TABLE XII.—*Diurnal Inequality at Kew*, 1890–1900. (*Unit* 0·1γ.)

Hour.	*N.*		*W.*		*V.*	
	June.	Dec.	June.	Dec.	June.	Dec.
1	+54	0	−24	−31	+6	+4
2	+**47**	−**1**	−40	−17	−**2**	+2
3	+49	+9	−53	−10	+1	+1
4	+58	+26	−93	−5	+4	+2
5	+**67**	+37	−169	−**3**	+**14**	+3
6	+38	+47	−244	−11	+7	−1
7	−14	+**52**	−284	−19	−1	−5
8	−79	+40	−**292**	−31	−28	−9
9	−146	+14	−248	−**40**	−69	−20
10	−203	−37	−132	−11	−114	−**33**
11	−**222**	−75	+22	+31	−**158**	−32
Noon ...	−197	−**78**	+185	+77	−149	−31
1	−160	−60	+263	+**107**	−110	−17
2	−90	−47	+**279**	+85	−48	+4
3	−26	−30	+242	+65	+4	+16
4	+17	−11	+184	+38	+53	+**25**
5	+69	+1	+123	+15	+90	+23
6	+114	+19	+91	+5	+100	+20
7	+**140**	+**26**	+65	−10	+**107**	+15
8	+128	+23	+50	−31	+101	+10
9	+116	+18	+39	−48	+78	+6
10	+90	+14	+36	−**56**	+56	+6
11	+77	+16	+9	−50	+36	+6
12	+67	+2	−10	−50	+24	+5

occurs during the night. In this connection several points have to be remembered. Diurnal inequalities may be expected to follow solar rather than mean time. On the average February day the sun is fourteen minutes after the clock, while on the average November day it is nearly fifteen minutes before the clock. Accordingly, if the diurnal inequality of a magnetic element were a simple sine wave of twenty-four-hour period obeying local solar time, we

should expect the G.M.T. hour of a maximum or minimum to be almost half an hour later in February than in November. In reality, of course, the maximum or minimum in the regular diurnal variation will in fifty-nine cases out of sixty occur at an intermediate minute, rather than an exact hour. But when hourly values only are recorded, the maxima and minima appear of necessity at exact hours. Thus a change of thirty minutes in the true time of a maximum or minimum will in tables such as XI. and XII. produce either no apparent change in the time or else a change of a full hour.

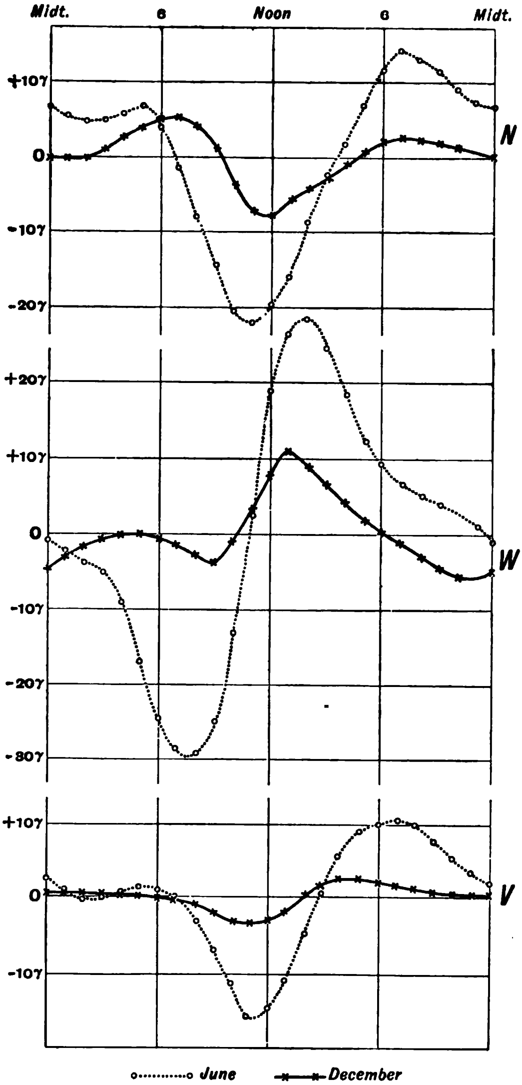


FIG. 7.—KEW QUIET DAY DIURNAL INEQUALITY.

While differences in the G.M.T. hours of maxima and minima in different months are doubtless influenced by the difference between solar

and mean time, this is not the sole or even the principal cause of such differences. The sun is less than one-half minute behind the clock on the average June day, and less than four minutes in advance on the average December day. But Tables XI. and XII. disclose differences between the hours of maxima and minima in June and December immensely greater than five minutes. For instance, the morning minimum (extreme easterly position) in *D* is seen at 7 a.m. in June, but at 9 a.m. in December.

In this and some other cases the phenomenon is probably related in some way to the time of sunrise.

At all events, while the extreme easterly position in the morning appears at Kew at 9 a.m. from October to February, it is seen at 8 a.m. in March, April and September, and at 7 a.m. from May to August, thus advancing with the hour of sunrise.

Inspection of Tables XI. and XII. or figures 6 and 7 discloses differences in the actual type of the inequalities in the two months. In *W*, for instance, we see in June a continual rise from a minimum at 8 a.m. to a maximum at 2 p.m., and a continual fall from 2 p.m. to 8 a.m. In December, however, there are two unmistakable minima at 9 a.m. and 10 p.m.—the latter, though the principal minimum in December, being wholly unrepresented in June—and two unmistakable maxima at 1 p.m. and 5 a.m.

In *D*, *W*, *H* and *I* at Kew there is only one distinct maximum and minimum in midsummer months; the equinoctial months show more or less distinct evidence of a second maximum and minimum, while in the midwinter months the double daily oscillation is unmistakable.

In *N* and *T* a double oscillation seems recognisable in most if not all months of the year.

In *V* a double oscillation is clearly apparent in the summer months, but not at midwinter.

In considering the reality of the existence of an

apparent maximum or minimum, the fact that there are limitations to the accuracy of all observational data must be borne in mind. The data of Tables XI. and XII. were derived from five quiet days for each month of eleven years, so that only fifty-five days actually contributed to each inequality. The H and V curves were not read to nearer than 1γ, while the unit in the inequalities of these and the other force components is $0{\cdot}1\gamma$. Thus an irregularity of even 5γ in the value of H or V for a single hour would mean 1 in the last unit in the tables. Even quiet days are seldom free from all trace of irregular disturbance, and to make certain of eliminating completely "accidental" irregularities in figures taken out to $0{\cdot}1\gamma$ we should have to employ a considerably larger number of days. When a slight want of smoothness appears in successive hourly values—*e.g.* between 8 and 10 p.m. in June in the case of D, or between 9 and 12 p.m. in December in the case of H—we have to be guided by the results from adjacent months. In the two cases mentioned the irregularities seem to be really accidental and do not signify the occurrence of a real maximum or minimum.

As we shall see in Chapter VII., the diurnal inequality does not as a rule present a close approach to a regular harmonic oscillation of twenty-four-hour period. Like any other continuous function periodic in a day, it can be represented by a series of simple harmonic terms, or Fourier waves, the largest period being twenty-four hours and the others sub-multiples thereof. The fact that the diurnal inequality of a particular element shows in some months only one maximum and minimum may mean, of course, that the twenty-four-hour term is largely dominant, but it generally does mean only that the times of maximum and minimum in the different Fourier waves are such that maxima of the principal terms occur near one hour of the day, thus reinforcing one another,

while minima occur near another hour. Maxima and minima of the shorter period terms often tend to neutralise one another. This is the real explanation of the prominence of the early afternoon maximum—extreme westerly position—in *D*. The twenty-four and twelve-hour waves greatly reinforce one another from 1 to 2 p.m., whereas in the corresponding early morning hour they tend to neutralise one another.

Table XIII. shows how the range of the regular diurnal inequality at Kew on quiet days varies with the season of the year. *Range* in this table means the difference between the two extreme hourly values.

TABLE XIII.—*Kew Diurnal Inequalities on Quiet Days* (1890–1900).

Month.	Range.				Average departure from mean.			
	D.	*I.*	*H.*	*V.*	*D.*	*I.*	*H.*	*V.*
	′	′	γ/10.	γ/10.	′	′	γ/10.	γ/10.
January	4·07	0·98	153	65	0·99	0·19	27	18
February	4·76	1·01	167	102	1·28	0·23	37	24
March	8·82	1·38	256	199	1·84	0·34	63	42
April	10·57	1·86	357	252	2·08	0·47	90	55
May	10·92	2·05	381	314	2·22	0·51	98	72
June	10·62	2·02	386	265	2·37	0·51	96	57
July	10·18	2·05	383	283	2·22	0·52	99	64
August	11·01	2·15	377	233	2·29	0·53	95	52
September	9·76	1·98	348	204	2·04	0·47	82	48
October	7·51	1·57	272	152	1·64	0·40	70	34
November	4·75	1·27	200	93	1·11	0·30	45	19
December	3·34	0·63	106	58	0·77	0·14	20	12
Means	8·03	1·58	282	185	1·74	0·38	68	42

As already explained, the extreme values of an element seldom occur exactly at an hour G.M.T.; thus the range derived from hourly measurements is less as a rule than the true natural range (*i.e.* the range one would get if one tabulated the curves at an infinite number of equally spaced intervals throughout the day). It is rare, however, for curves representing magnetic diurnal inequalities to be

sharply peaked, and the change of an element within half an hour of its time of reaching an extreme position for the day is usually small; thus the true inequality range would seldom exceed that derived from hourly values by more than two or three per cent.

While the range gives a very fair idea of the relative importance of a diurnal inequality possessing only one maximum and minimum, it is less satisfactory when there is a double daily oscillation. A better idea is then derived from the average hourly departure from the daily mean, *i.e.* the quantity obtained by dividing by twenty-four the sum of the twenty-four-hourly departures from the daily mean taken irrespective of sign. This explains the occurrence of this quantity in Table XIII.

The arithmetic mean of the ranges for the diurnal inequalities of the twelve months is not the same as the range in the mean diurnal inequality for the whole year. The two quantities would agree only if the hours of maximum and minimum were the same for all months. Except in this extreme case the arithmetic mean of the twelve monthly ranges necessarily exceeds the range in the mean diurnal inequality for the year.

If we take the means in the last line of Table XIII., we find for the ratio borne by the range to the average departure from the mean 4·61 for D, 4·11 for I, 4·12 for H, and 4·46 for V. In the case of a simple harmonic wave of twenty-four-hour period in which the maximum and minimum fall at exact hours G.M.T., the value of the above ratio would be 3·16.

The most conspicuous features of Table XIII. are the prominence of the December minimum, the rapidity of the rise from February to March and of the fall from October to November, and the smallness of the variation near midsummer.

The results for the D, I and V ranges suggest, in fact, a secondary minimum at midsummer, but its existence is

doubtful, especially in view of the results for the average departure from the mean.

Curves like those of Figs. 6 and 7 show only the diurnal change in single elements. The most complete representation would be that afforded by a model obtained by drawing from a fixed point, for each hour of the twenty-four, a series of lines representing in direction and intensity the resultant force to which the diurnal inequality may be ascribed. If ΔN, ΔW and ΔV denote the departures of N, W and V at any common hour from the mean value for the day, the vector in question has ΔN, ΔW and ΔV for its three rectangular components. Such a model would have to be seen to be fully realised. We can, however, obtain an idea of its character from the projections of the vector in question on the three co-ordinate planes. The projection in the horizontal plane has ΔN and ΔW for co-ordinates; the projection in the vertical plane which contains the geographical meridian has ΔN and ΔV for its co-ordinates, and the projection in the vertical plane perpendicular to the meridian has ΔW and ΔV for its co-ordinates.

Instead of actually drawing the vectorial lines in these planes, it is simpler to draw a free-hand curve through their extremities, attaching numerals indicating the hour at the points where the representative vectors abut on the curve. This is done in the curves of Fig. 8, which answer to the mean diurnal inequality for the year at Kew. The line drawn from the origin of co-ordinates to a point marked n represents in magnitude and direction the force at hour n—in the plane to which the curve belongs—to which the diurnal inequality may be ascribed. To avoid the use of the letters a.m. and p.m., n is reckoned from 0 to 24. The term *vector diagram* has usually been confined to the curve in the horizontal plane—or NW curve—but with the specification of the plane of the two components it seems equally applicable to all three

curves. The arms of the cross formed by the co-ordinate axes in Fig. 8 represent in each case 10γ.

The *NW* diagram in Fig. 8 is described continuously in a clockwise direction. Near midnight, however, the angular velocity is relatively small, and the area swept out by the vector in the twelve night hours, 18 to 6, is very much less than that described during the day. The angular velocity is most rapid between 9 a.m. and 1 p.m., and the vector has its greatest value about the latter hour. The vector passes through geographical south before 11 a.m., and so at this hour is well in advance of the sun. It crosses the magnetic meridian about 10 h. 20 m. and again just before 19 h. The curve shows a small bay or re-entrant portion between 0 and 3 a.m. When Kew vector diagrams are drawn for individual months the midwinter curves show an actual loop near midnight.

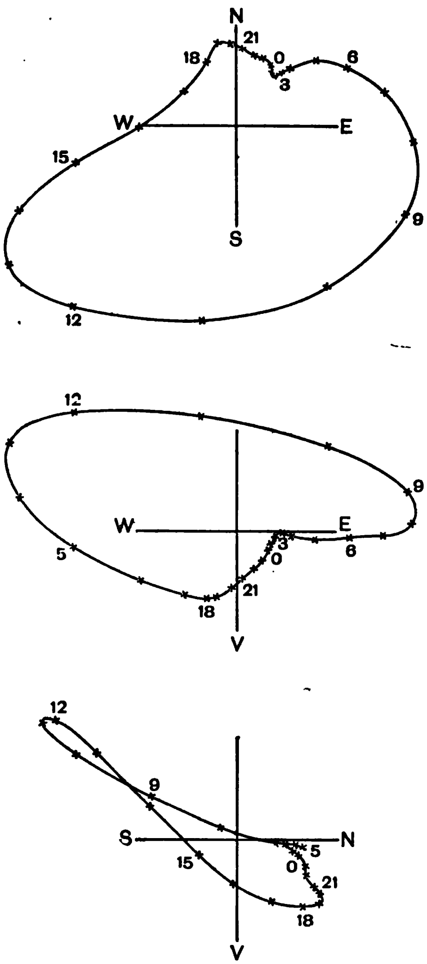


Fig. 8.—Kew Quiet Day Vector Diagrams.

The *WV* diagram in Fig. 8 represents the phenomena in a plane containing the line *WE* of the *NW* diagram,

and perpendicular to the plane of that diagram, the *V* axis being directed downwards, *i.e.* towards the earth's centre. It is described continuously in one direction. The part described between hours 9 and 18 is roughly elliptical in outline, the vector having its greatest value near 1 p.m. The diagram is, as it were, dinted in during the night hours.

The *NV* diagram is of a remarkably elongated, narrow type. The portion answering to hours 2 to 5 is omitted, as it could not be shown distinct from the portion answering to the hours 5 to 7 with which it practically coincides. The changes in *V* on quiet days are so small near midnight that it is open to doubt whether accidental features have been wholly got rid of. As the numerical figures stand, it is not possible to say whether the portion of curve representing hours 2 to 6 forms a beak or a very narrow loop. Between hours 9 to 14 there is a distinct loop. During the early afternoon the curve presents a close approach to a straight line, a fact first pointed out by Mr. R. B. Sangster[1] as characteristic of several stations. In all the cases he examined Mr. Sangster found the straight line to which the curve most closely approximated to be nearly perpendicular to the earth's polar axis. In the present instance the straight line joining the points of the diagram which answer to hours 12 and 17 is inclined to the earth's axis at $84\frac{1}{3}°$, while the line joining the points which answer to hours 13 and 16 makes with the axis an angle of $87\frac{1}{2}°$. Both these lines are included between the horizontal and the perpendicular on the axis.

Fig. 9 shows the great variation in the shape of the *NW* diagram at different seasons of the year. It gives side by side diagrams for Kew and Falmouth for May, September and January. The diagrams are drawn to a

[1] *Proc. Roy. Soc.*, A., 1910, **83**, p. 428.

common scale; in each case the arms of the cross formed by the co-ordinate axes represent 10γ. The line drawn from the origin of co-ordinates to M represents the magnetic meridian. Considering that the two stations are more than 200 miles apart, the close resemblance between

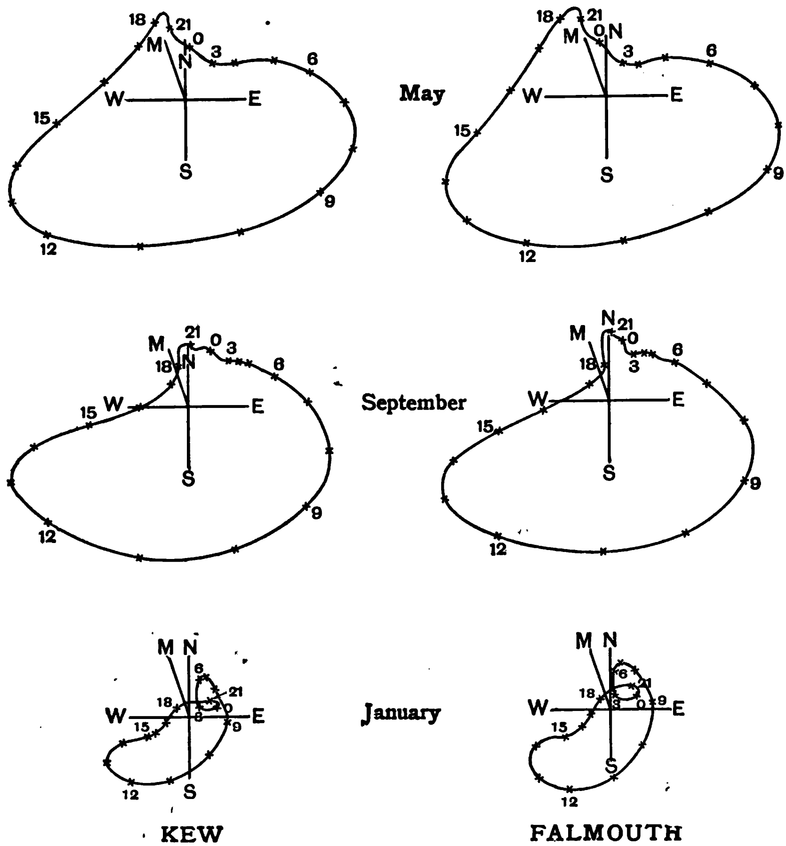


FIG. 9.—QUIET DAY VECTOR DIAGRAMS.

their diagrams is very striking. Terrestrial Magnetism is in this respect very unlike meteorological elements as observed at the earth's surface; these usually exhibit marked local peculiarities.

There are certain features common to all the diagrams in

Fig. 9. The greater part of the area enclosed by the curve is described by the vector during daylight hours. The vector is largest about 1 p.m. and its angular velocity is greatest between 9 a.m. and 1 p.m. It passes through geographical south in advance of the sun. In the May diagram—and the same is true of the diagrams for June, July and August—there is a species of beak answering to hours 17 to 23. In September this beak becomes less prominent, while a second beak tends to manifest itself in the early morning. From October to March there is a loop in the diagram during the midnight hours, which is well seen in the January curves.

The area enclosed by the *NW* vector diagram is not a measure of the mean value of the force to which the diurnal changes in the longitudinal plane are due, but rather of the square of this quantity. This accounts for the extreme smallness of the area enclosed by the January as compared to the other curves. Small as is the area bounded by the January diagram, it is considerably larger than that bounded by the December diagram. In point of area the January diagram is followed in ascending order by the diagrams for February and November. Following these, but at a considerable interval, come the March and October diagrams, which are roughly equal.

CHAPTER V

DIURNAL INEQUALITY ON ORDINARY DAYS

TABLE XIV. gives the diurnal inequality of declination at Kew for each month of the year derived from the *ordinary* days of the eleven years 1890 to 1900—*i.e.* all days with the exception of those highly disturbed. The disturbed days omitted numbered 209, an average of nineteen a year. Distinct maxima and minima are in heavy type, and the last line gives the ranges as derived from the hourly values.

TABLE XIV.—*Diurnal Inequality of Declination at Kew.* (*Ordinary Days,* 1890–1900.)

Hour.	Jan.	Feb.	March.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
	′	′	′	′	′	′	′	′	′	′	′	′
1	−1·24	−1·74	−1·75	−1·42	−1·38	−1·24	−1·28	−1·66	−1·88	−1·62	−1·31	−1·18
2	−1·01	−1·46	**−1·68**	−1·47	−1·58	−1·48	−1·63	−1·86	−1·93	−1·49	−0·99	−0·84
3	−0·80	−1·34	−1·70	−1·63	−1·86	−1·88	−1·93	−2·13	−2·10	−1·41	−0·81	−0·66
4	−0·76	−1·25	−1·72	−1·93	−2·37	−2·61	−2·53	−2·49	−2·24	**−1·31**	**−0·78**	−0·48
5	−0·72	−1·24	−1·75	−2·19	−3·26	−3·71	−3·68	−3·19	−2·35	**−1·31**	−0·79	−0·47
6	**−0·70**	−1·22	−1·79	−2·74	−3·98	−4·61	−4·43	−3·88	−2·65	−1·37	−0·85	**−0·46**
7	−0·74	**−1·16**	−2·27	−3·64	**−4·46**	**−4·91**	**−4·54**	**−4·21**	**−3·07**	−1·72	−0·85	−0·49
8	**−0·85**	**−1·26**	**−3·02**	**−4·22**	−4·17	−4·61	−4·19	−3·82	−3·06	**−2·40**	**−1·12**	−0·53
9	−0·63	−1·17	−2·76	−3·53	−2·85	−3·39	−3·07	−2·30	−1·85	−2·27	−1·11	**−0·54**
10	+0·36	−0·05	−0·94	−1·22	−0·27	−0·99	−0·91	+0·34	+0·60	−0·47	+0·01	+0·19
11	+1·61	+1·78	+2·02	+2·04	+2·76	+2·00	+1·90	+3·29	+3·46	+2·45	+1·76	+1·32
Noon	+2·78	+3·32	+4·77	+5·19	+5·24	+4·61	+4·56	+5·87	+5·75	+4·58	+3·18	+2·41
1	**+3·26**	**+4·08**	**+6·06**	**+6·73**	**+6·20**	+5·82	+5·92	**+6·80**	**+6·42**	**+5·33**	**+3·61**	**+2·86**
2	+2·66	+3·99	+5·85	+6·40	+5·86	**+6·01**	**+6·05**	+6·19	+5·53	+4·74	+3·06	+2·43
3	+1·75	+3·01	+4·41	+4·79	+4·55	+5·14	+5·04	+4·57	+3·81	+3·48	+2·13	+1·77
4	+1·23	+1·82	+2·52	+3·05	+3·07	+3·81	+3·52	+2·54	+2·02	+1·94	+1·47	+1·22
5	+0·80	+1·12	+0·99	+1·50	+1·74	+2·30	+2·03	+0·91	+0·73	+0·94	+0·84	+0·67
6	+0·30	+0·55	+0·24	+0·31	+0·62	+1·17	+0·93	+0·02	+0·08	+0·28	+0·27	+0·13
7	−0·28	−0·04	−0·34	−0·34	−0·06	+0·41	+0·36	−0·22	−0·36	−0·37	−0·29	−0·42
8	−0·88	−0·66	−0·76	−0·71	−0·38	+0·10	+0·10	−0·44	−0·82	−1·01	−0·89	−0·91
9	−1·37	−1·33	−1·24	−0·96	−0·58	−0·16	−0·14	−0·67	−1·16	−1·52	−1·47	−1·37
10	**−1·66**	−1·74	−1·55	−1·26	−0·77	−0·32	−0·38	−0·98	−1·43	−1·81	−1·73	**−1·60**
11	−1·64	−1·96	−1·68	−1·36	−0·96	−0·61	−0·70	−1·21	−1·69	**−1·90**	**−1·76**	−1·58
12	−1·49	**−1·98**	**−1·80**	−1·40	−1·16	−0·93	−0·98	−1·45	−1·85	−1·77	−1·63	−1·50
Range	4·92	6·06	9·08	10·95	10·66	10·92	10·59	11·01	9·49	7·73	5·37	4·46

The extent to which the *type* of the inequality varies throughout the year is most readily grasped by considering Fig. 10, where the *D* inequality for March is drawn exactly to the scale shown, while the inequalities for June and December are represented on scales so related that the mean length of the twenty-four hourly ordinates is the same as for March. It will be seen that the difference in type is mainly confined to the hours between 7 p.m. and 9 a.m. when the changes are least rapid.

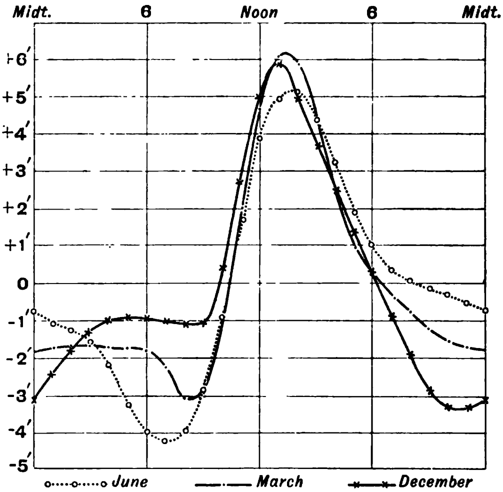


FIG. 10.—KEW DECLINATION. ORDINARY DAYS.

Comparing the ranges in Tables XIII. and XIV. we see that from October to March the ordinary day range is decidedly larger than the quiet day range. In summer, however, the differences between the two sets of ranges are not great, and the quiet day range is not always the smaller. It would, however, be a mistake to conclude that all difference between the ordinary and quiet day inequalities tends to disappear in summer. That this is not the case is apparent on consultation of Table XV. and Fig. 11.

Table XV. gives for each month of the year at Kew the ratio borne by the range of the ordinary day inequality to that of the quiet day, and likewise the ratio borne by the average departure from the mean in the former inequality to the corresponding quantity in the quiet day inequality.

TABLE XV.—(*Ordinary Day/Quiet Day*) *Ratios.*

Month.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
Ranges	1·21	1·27	1·03	1·04	0·98	1·03	1·04	1·00	0·97	1·03	1·13	1·33
Mean departures	1·25	1·28	1·22	1·20	1·13	1·10	1·14	1·11	1·16	1·21	1·23	1·41

If the two sets of inequalities were of the same type the range ratios and mean departure ratios should be identical. The mean departure ratio is, however, invariably the larger, and the differences between the two ratios are at least as conspicuous in summer months, when the range ratio approaches unity, as at midwinter when the range ratio is largest. The fact that the mean departure ratio is the larger implies that on ordinary days the average intensity of the force to which the inequality is due is in excess of the corresponding average intensity on quiet days to a greater extent than one would conclude from a study of ranges only. The intensity of in-

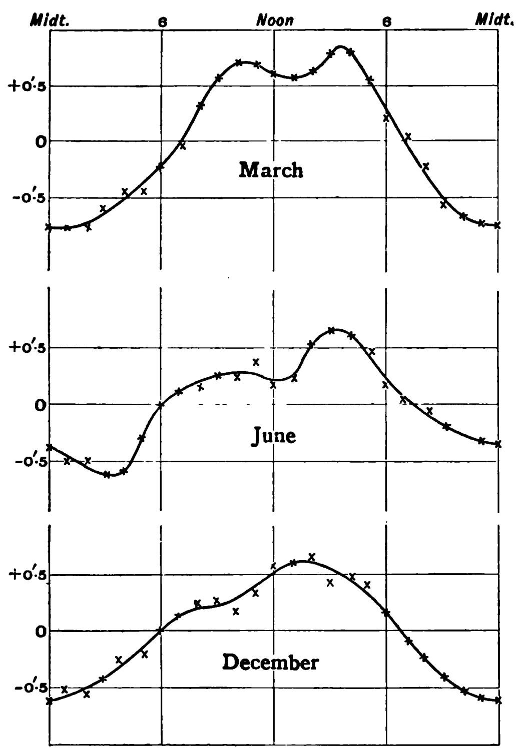


FIG. 11.—KEW DECLINATION DIFFERENCE CURVES.

equality forces at night is not so small compared to the intensity during the day, on ordinary days as on quiet days.

Fig. 11 illustrates the differences between ordinary and quiet day D inequalities at Kew in March, June, and December, taken as representative of equinox, summer and winter. The ordinate of the curve represents the algebraic excess of the hourly value of the ordinary day diurnal inequality over that of the quiet day inequality. These *difference curves* have the following ranges: March $1'\cdot 57$, June $1'\cdot 30$, and December $1'\cdot 24$, representing respectively 18, 12 and 37 per cent. of the corresponding quiet day ranges. The December difference curve shows only one distinct maximum and minimum. The other two difference curves show two decided maxima during the day hours with an unmistakable intervening depression; they do not resemble the inequality curves for either ordinary or quiet days.

The difference between ordinary and quiet day inequalities varies not merely with the station but also with the magnetic element considered. This is illustrated by the data for Pavlovsk in Table XVI. At this station quiet days are selected after Wild's method, and being fewer in number than those selected by the Astronomer Royal, represent presumably a still quieter average set of conditions. Magnetic disturbances on the other hand are larger and more numerous at Pavlovsk than at Kew. The table gives the average ranges of the diurnal inequalities of D, H and V from all and from quiet days for the eleven-year period 1890 to 1900. The range assigned for instance to January is the arithmetic mean of the ranges obtained for the eleven Januarys treated separately. It is thus probably a little greater than the range of the diurnal inequality that would be obtained by combining the January days of all the eleven years. The fact that all and not merely ordinary days are included in one set of

inequalities may be expected to slightly increase the difference between the two sets.

TABLE XVI.—*Pavlovsk Inequality Ranges*, 1890–1900.

Month.	D.		H (unit 0·1 γ).		V (unit 0·1 γ).	
	All.	Quiet.	All.	Quiet.	All.	Quiet.
	′	′				
January ...	4·93	2·96	120	120	148	43
February ...	6·15	4·20	196	169	274	52
March ...	8·58	8·73	316	307	291	94
April... ...	10·93	11·28	464	419	238	130
May	12·18	12·89	470	454	263	134
June	12·27	13·28	493	446	203	123
July	11·82	12 31	486	420	227	131
August ...	11·38	11·70	442	397	186	105
September .	8·70	9·37	390	375	229	91
October ...	6·87	6 91	318	308	198	74
November..	5·54	3·95	167	175	183	46
December...	4·63	2·66	109	104	143	41
Year ...	7·41	7·94	295	287	192	70

The declination ranges show some of the phenomena already described at Kew in an enhanced degree. The quiet day range is much reduced towards midwinter, but is distinctly in excess of the all day range in midsummer. Consequently the seasonal variation in the range is much more conspicuous on quiet than on all days.

In H the range seems larger for all than for quiet days, but the difference is small, and is less decided in winter than in summer.

In the case of V the difference between quiet and all day ranges is simply enormous. Towards midwinter the quiet day range is only about a quarter of the other.

CHAPTER VI

DIURNAL INEQUALITY ON DISTURBED DAYS

WHEN deriving diurnal inequalities of declination for ordinary days at Kew from the records of the eleven years, 1890 to 1900, I omitted the curves of 209 days as being highly disturbed. It occurred to me to try whether these 209 days when treated separately gave anything resembling a regular diurnal inequality. If magnetic disturbance were of a purely accidental character, what we should expect to obtain in this way would be the ordinary diurnal inequality, with irregularities superposed on it, which would be less and less prominent as the number of disturbed days was increased. For a small number of disturbed days the irregularities might well be so prominent as to hide the regular diurnal inequality.

The practice previously followed at Kew had been to smooth the traces when disturbed or oscillatory by drawing a free-hand curve. The 209 days' curves above referred to had really been put aside because their irregularities were such that it was impossible to draw a free-hand curve satisfactorily. When they were ultimately taken in hand, the ordinates of the actual traces were measured exactly at the hour G.M.T. In the circumstances it was a great surprise when definite inequalities made their appearance not merely from the 209 days combined, but even from the limited number belonging to each of the twelve months of the year.

Table XVII. contrasts the mean diurnal inequalities for the whole year derived from these 209 highly disturbed days with those from the 660 quiet days selected for the same years by the Astronomer Royal.

TABLE XVII. *Mean Diurnal Inequalities for the Year at Kew from Disturbed (d) and Quiet (q) Days.*

Hour.	*D.*		*I.*		*H.*		*N.*		*W.*		*V.*	
	d.	*q.*	*d.*	*q.*	*d.*	*q.*	*d.*	*q.*	*d.*	*q.*	*d.*	*q.*
	′	′	′	′	γ/10	γ/10	γ/10	γ/10	γ/10	γ/10	γ/10	γ/10
1	−4·85	−0·90	−0·51	−0·26	+2	+42	+78	+54	**−246**	−33	−176	+12
2	−4·03	−0·91	−0·75	−0·23	+25	+36	+88	+48	−197	−36	−211	+6
3	−3·55	−1·01	−1·01	−0·28	+58	+37	+112	+51	−168	−40	−222	+8
4	−1·97	−1·29	−1·02	−0·24	+47	+38	+76	+57	−86	−54	**−253**	+5
5	−0·44	−1·77	**−1·05**	−0·23	+55	+39	+60	+65	−6	−78	−246	+7
6	−0·48	−2·31	−0·75	−0·14	+17	+24	+24	+59	−19	−110	−229	+5
7	−0·40	−2·80	−0·19	+0·08	−46	−8	−38	+87	−34	−145	−178	+3
8	−0·81	**−3·06**	+0·53	+0·42	−142	−65	−123	−14	−83	**−175**	−151	−10
9	−0·05	−2·53	+1·23	+0·81	−243	−182	−281	−86	−75	−168	−140	−40
10	+1·70	−0·72	**+1·53**	**+1·00**	**−285**	**−179**	−299	−160	+2	−90	−134	−82
11	+3·83	+1·71	**+1·53**	+0·90	−274	−175	**−322**	**−194**	+113	+35	−109	−112
Noon	+6·11	+3·91	+1·11	+0·55	−197	−124	−285	−180	+252	+162	−73	**−114**
1	+7·04	**+4·84**	+0·65	+0·24	−90	−66	−197	−140	+331	**+226**	+18	−84
2	**+7·11**	+4·38	+0·14	+0·06	+37	−19	−77	−87	**+372**	+217	+139	−32
3	+5·78	+3·14	+0·16	−0·03	+89	+12	−6	−38	+320	+163	+270	+16
4	+4·03	+1·75	+0·17	−0·05	+133	+27	+63	−2	+244	+97	+381	+47
5	+2·63	+0·75	−0·12	−0·17	+186	+48	+136	+84	+189	+52	**+399**	+63
6	+0·37	+0·19	−0·16	−0·30	+183	+69	+169	+63	+73	+30	+382	**+65**
7	−1·42	−0·10	−0·35	**−0·42**	**+188**	**+83**	**+202**	**+81**	−16	+20	+324	+62
8	−3·45	−0·33	−0·11	−0·41	+108	+78	+158	+80	−143	+6	+219	+54
9	−4·48	−0·53	−0·08	−0·39	+60	+72	+128	+77	−210	−5	+135	+46
10	−3·88	−0·66	−0·08	−0·34	+19	+60	+79	+68	−191	−16	+17	+36
11	**−4·89**	−0·80	−0·38	−0·33	+43	+56	+118	+66	−236	−24	−35	+26
12	−3·89	−0·95	−0·54	−0·29	+27	+47	+87	+60	−190	−34	−127	+18
Range	12·00	7·90	2·58	1·42	473	262	524	275	618	401	652	179
Average departure ...	3·22	1·72	0·59	0·34	106	64	131	75	158	84	190	40

Before discussing Table XVII. a few explanations are necessary. The number of quiet days was the same for each month of the eleven years. The disturbed days were much more numerous in some months than in others, and in some years than in other years. The mean diurnal inequality for the year was always obtained by combining mean diurnal inequalities for the individual months, so that each month of the twelve had the same weight. But while every year contributed the same quota of quiet days for each month, some years contributed much more than their share of disturbed days, and these years

had thus enhanced weight in the disturbed day inequalities. For instance, 1890 and 1900 between them contributed only fourteen highly disturbed days, while 1892 contributed thirty, and 1896 no fewer than thirty-nine. As we shall see in Chapter XIV., the amplitude of the diurnal inequality increases with sunspot frequency, and on the whole the disturbed days were most numerous in years of many sunspots. Thus one would not have been surprised if the ranges from the disturbed day inequalities in Table XVII. had exceeded those from the quiet days. The actual differences, however, are far too great to be accounted for by mere differences in sunspot frequency. The disturbed day ranges are much in excess of the quiet day ranges for the years 1892 to 1895, during which the sunspot frequency was a maximum.

A second point calling for attention is this: The Astronomer Royal's quiet days present at least a fair approach to the ideal quiet day, which is totally free from irregular movements. Thus, presumably, the inequalities derived from them are not widely different from those which ideally quiet days would give. The disturbed days, on the other hand, varied greatly as to the intensity of disturbance. A few were highly disturbed throughout the whole twenty-four hours, but the majority were highly disturbed only for a portion of the day, sometimes only a small portion.

Thus the standard of disturbance to which the disturbed day inequalities in Table XVII. relate was wholly arbitrary, and did not distantly approach the extreme intensity of a magnetic storm of the first order.

The extreme values in each inequality in Table XVII. are in heavy type. The ranges in the second last line are derived from these. The last line gives the average departure from the daily mean.

The disturbed day inequalities present many minor irregularities, but there is every indication that if the

number of disturbed days had been much larger, the resulting inequalities would have presented the same general features, while exhibiting a similar smoothness to inequalities derived from quiet or ordinary days. The difference of type between the disturbed and quiet day inequalities is considerably less for H and N than for D and W, and less for the two latter elements than for V and I. As regards range, the increase for disturbed days in Table XVII. is some 50 per cent. in D and W, some 80 per cent. in H and N, some 90 per cent. in I, but over 260 per cent. in V. The increase in the average departure from the mean is in general relatively larger that that in the range.

TABLE XVIII.—*Kew Diurnal Inequalities on Disturbed Days.*

Month.	Range.			Average departure from mean.		
	D.	*H.*	*V.*	*D.*	*H.*	*V.*
	′	γ/10.	γ/10.	′	γ/10.	γ/10.
January	10·90	207	235	2·71	45	78
February	11·05	381	845	2·99	81	227
March	14·95	322	682	4·07	71	192
April	16·60	566	620	4·79	137	185
May	15·70	794	984	4·42	186	287
June	17·34	1121	959	3·84	232	265
July	13·24	1241	1342	3·70	309	337
August	14·62	1038	1097	3·26	240	221
September... ...	14·42	531	720	3·66	129	166
October	12·92	354	334	2·91	87	105
November... ...	12·38	366	629	3·22	74	162
December	11·88	303	382	2·72	64	97

Table XVIII. gives the ranges and the average departures from the mean for the diurnal inequalities derived from the disturbed days of each of the twelve months of the year. The data should be compared with those for quiet days in Table XIII., p. 43. Owing to the fewness of the disturbed days and the method of their selection, the standard of disturbance for adjacent months in Table XVIII. probably differs widely. Thus too much significance must not be attached to individual figures.

There are, however, some curious differences, probably real, between the phenomena exhibited by different elements. The difference between winter and summer *D* ranges is markedly less for disturbed than for quiet days. In Table XVIII. the largest range is only 1·6 times the smallest, whereas the largest range in Table XIII. is 3·3 times the smallest. In *H* and *V*, on the other hand, the ratio borne by the largest to the smallest range is greater for disturbed than for quiet days.

While the *D* range in Table XVIII. is actually less for

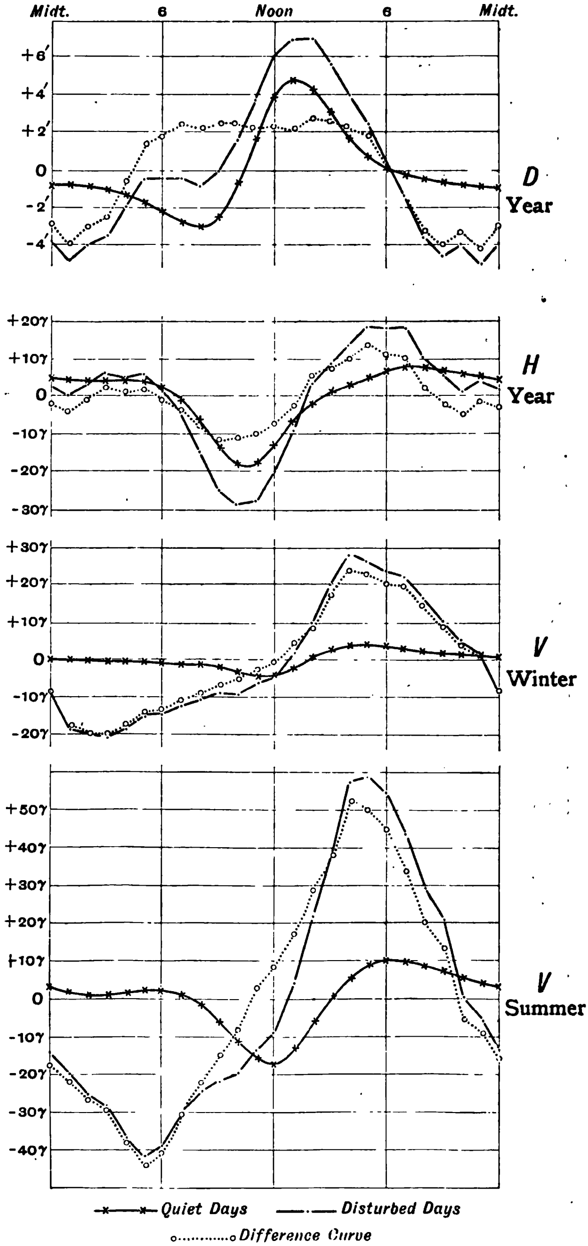


FIG. 12.—KEW DIURNAL INEQUALITIES.

July and August than for March, the July and August H ranges are from three to four times the March range, and in V the differences though less than for H are in the same direction.

Fig. 12 shows the mean diurnal inequality for the year from quiet and disturbed days in D and H, and the mean diurnal inequalities in V for winter (November to February) and summer (May to August). The figure also contains *difference curves*, the ordinates of which represent the algebraic excess of the disturbed over the quiet day values. In H—and the same is true of N—the differences in type between the three curves are trifling. In D, however—and the same may be said of W—the difference curve is quite unlike the quiet day curve; between the rapid morning rise and evening fall in the difference curve there is an elevated plateau, not represented on quiet days. Still more striking is the difference between the quiet and disturbed day curves for V. On quiet days, more especially in winter, the changes in V during the night hours are minute; but on disturbed days the changes during the night are similar in size and rapidity to those during the day. The V difference curve is much more symmetrical than the quiet day curve. Instead of the rapid fall and rise exhibited by the quiet day curve during the midday hours, there is in the difference curve an uninterrupted rise from an early morning minimum to an afternoon maximum.

The figure also serves to bring out the enormous increase caused by disturbance in the V range.

Fig. 13 contains NW, WV and NV vector diagrams representing the disturbed day diurnal inequality at Kew for the entire year; these should be compared with the corresponding quiet day diagrams in Fig. 8, p. 46.

In the case of the disturbed day diagrams, it appeared advisable to connect the points answering to the hourly values by straight lines, as the data were not regular

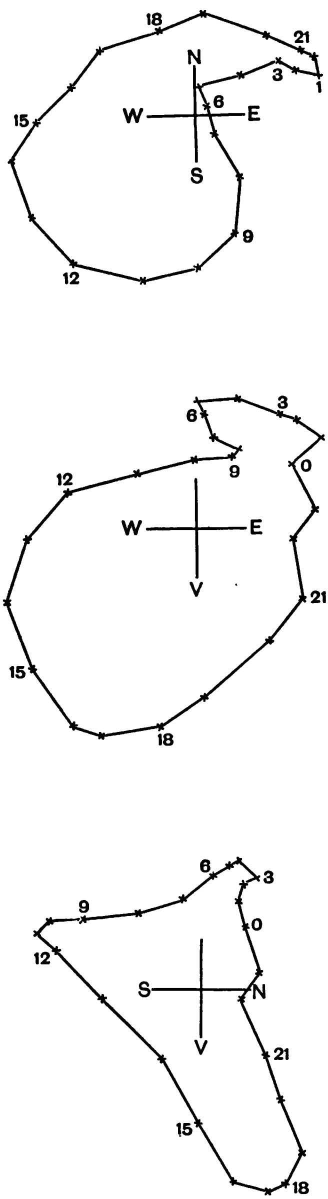


Fig. 13.—Kew Disturbed Day Vector Diagrams.

enough to admit of free-hand curves being drawn satisfactorily.

The arms of the cross formed by the intersection of the co-ordinate axes represent 10γ, as in the quiet day diagrams. This merits special attention as the two sets of diagrams are not drawn to a common scale.

To avoid confusing the *NW* diagram in Fig. 13, the results from hours 0 and 22 were disregarded. It is open to doubt whether there is, or is not, a small loop near midnight.

The difference of shape between the disturbed and the quiet day *NW* and *WV* diagrams arises partly from the fact that the amplitude of the *W* diurnal inequality is less increased by disturbance than the amplitudes of the *N* and *V* inequalities. Another cause of difference is that the excess of the angular velocity of the vector by day over that by night is much less for the disturbed than for the quiet day diagrams.

The disturbed day *NV*

diagram is practically a straight line between hours 11 and 14 and again between hours 14 and 16, but the two straight lines are sensibly inclined. The lines joining the points answering to hours 11 and 14, 12 and 14, 14 and 16, 11 and 16, and finally 12 and 16 make with the earth's axis the respective angles: 96°·8, 97°·0, 111°·4, 103°·3 and 104°·0. All these lines lie between the vertical and the perpendicular on the earth's axis. It would thus appear that while the afternoon portion of the disturbed day *NV* diagram still possesses the feature discovered by Mr. Sangster, the straight line which most closely resembles it is inclined at a sensible angle to the corresponding straight line obtained for the quiet day diagram, the two lines lying on opposite sides of the perpendicular on the earth's axis.

A straight portion of a vector diagram implies a constant value in the component of the vector in the direction perpendicular to the straight portion.

Some properties of the diurnal inequality on disturbed days can be grasped more easily by considering the three dimensional movements of the vector.

Let ϕ denote the inclination to the geographical meridian of the vertical plane which contains the vector—measured positively from north to east—and let θ be the inclination of the vector to the vertical, directed downwards. Also let R denote the intensity of the vector, and ρ its component in the horizontal plane.

Employing ΔN, ΔW and ΔV in their usual senses, we have

$$\phi = \tan^{-1}(-\Delta W/\Delta N)\,;\ \rho = \sqrt{\Delta N^2 + \Delta W^2}\,;\ \theta = \tan^{-1}(\rho/\Delta V),$$
$$R = \sqrt{\Delta N^2 + \Delta W^2 + \Delta V^2} = \rho/\sin\theta = \Delta V/\cos\theta.$$

Table XIX. gives the hourly values of ϕ, θ, ρ and R for the mean diurnal inequality for the year, as derived from quiet days (q), the 209 disturbed days (d), and finally as answering to the difference between the disturbed and quiet day hourly values (d-q). The d-q vector thus represents the forces which when combined with those

giving the diurnal inequality on quiet days produce the disturbed day diurnal inequality.

To explain the table, suppose as an example $\phi=45°$, $\theta=50°$, $R=20\gamma$; then the force required to produce the departure from the mean value for the day which exists at the specified instant has an intensity of 20γ, has its horizontal component oriented in a *N.E.* direction, and is directed below ground, making with the horizontal an angle of 40° (*i.e.* 90°–50°).

TABLE XIX.—*Co-ordinates of Diurnal Inequality Force Vector at Kew.*

Hour.	ϕ.			θ.			ρ (unit 1 γ).			R (unit 1 γ.)		
	q.	*d.*	*d-q.*	*q.*	*d.*	*d-q.*	*q.*	*d.*	*d-q.*	*q.*	*d.*	*d-q.*
	°	°	°	°	°	°						
1...	31	72	84	79	124	131	6·3	25·8	21·4	6·4	31·2	28·5
2...	37	66	76	84	134	143	6·0	21·6	16·6	6·0	30·2	27·3
3...	38	56	64	87	138	149	6·5	19·8	13 7	6·5	29·7	26·4
4...	43	49	59	86	156	172	7·9	11·5	3·7	7·9	27·8	26·1
5...	50	6	266	86	166	164	10·2	6·0	7·2	10·2	25·3	26·3
6...	62	38	249	88	172	157	12·5	3·1	9·7	12·5	23·1	25·3
7...	76	138	236	89	164	144	15·0	5·1	13·4	15·0	18·5	22·5
8...	95	146	220	93	136	135	17·6	14·8	14·3	17·6	21·2	20·1
9...	117	162	213	102	120	120	18·9	24·3	17·2	19·3	28·0	19·9
10...	151	180	213	114	114	107	18·4	29·9	16·7	20·1	32·8	17·5
11...	190	199	211	120	108	89	19·7	34·1	15·0	22·7	35·8	15·0
Noon	222	221	221	115	101	73	24·2	38·0	13·8	26·8	38·7	14·4
1...	238	239	242	108	87	50	26·6	38·5	12·0	27·9	38·6	15·7
2...	248	258	274	98	70	42	23·4	38·0	15·5	23·6	40·4	23·1
3...	257	259	282	85	50	32	16·7	32·6	16·0	16·8	42·3	30·0
4...	269	284	294	64	33	26	9·7	25·2	16·1	10·8	45·7	37·1
5...	303	306	307	45	27	27	6·2	23·3	17·1	8·9	44·8	37·7
6...	335	337	338	47	26	20	7·0	18·4	11·4	9·5	42·4	33·7
7...	346	5	17	53	32	26	8·3	20·3	12·6	10·4	38·2	29·1
8...	356	42	62	56	44	46	8·0	21·3	17·2	9·7	30·6	23·6
9...	4	59	76	59	61	67	7·7	24·6	21·1	9·0	28·1	22·9
10...	13	68	86	63	85	96	7·0	20·7	17·5	7·9	20·7	17·6
11...	20	63	76	70	98	106	7·0	26·4	21·8	7·5	26·6	22·7
12...	30	65	80	75	121	132	6·9	20·9	15·8	7·1	24·5	21·5

The polar curve ρ, ϕ is the *NW* vector diagram. The value 4° at 9 p.m. under the heading q should be interpreted as 364° when comparing it with the value 356° assigned to 8 p.m., and similarly in other cases. The apparent discontinuity in ϕ between 4 and 5 a.m. in the

column headed $d-q$ signifies that ρ vanished and the ρ, ϕ curve crossed the geographical meridian.

On quiet days the ρ vector—to one regarding the horizontal plane from above—travels round persistently in a clockwise direction; but on disturbed days the motion is counter-clockwise between 1 and 5 a.m. These facts, of course, are shown in the *NW* vector diagrams in Figs. 8 and 13.

The disturbed day ρ vector is usually in advance of the quiet day vector. They are, however, almost coincident at noon and keep pretty close together until 6 p.m.

On quiet days θ has its minimum value at 5 p.m., rising slowly until 2 or 3 a.m., and then altering but little until 7 a.m. There is then a fairly rapid rise to a maximum at 11 a.m., followed by a steady fall to the minimum. The total range of θ is 75°, the value exceeding 90°—*i.e.* the vector being directed above ground—only from 8 a.m. to 2 p.m.

On disturbed days θ has the much wider range 146°; the rise from 6 p.m. to 6 a.m. and fall from 6 a.m. to 6 p.m. are uninterrupted. General information as to whether θ exceeds 90° or not can be derived from the *NV* diagrams in Figs. 8 and 13. The angle exceeds 90° when the vector in the *NV* diagram lies on the opposite side of *NS* to *V*.

The mean values of θ for the q, d, and $d-q$ columns are respectively 82°, 99°, and 94°. Thus the mean positions of the vector during quiet and disturbed days are about equally inclined to the horizon, but on opposite sides of it.

The disturbed day value of ρ exceeds the quiet day value except between 5 and 8 a.m. The disturbed day value of R is always the larger. On quiet days, owing to the small size of ΔV, there is generally much less difference between ρ and R than there is on disturbed days; ρ has its maximum at 1 p.m. both on quiet and disturbed

days, but the maximum of R is at 4 p.m. on disturbed days as against 1 p.m. on quiet days. If we call the twelve hours from 6 a.m. to 6 p.m. "day," and the remaining twelve hours "night," we obtain the mean values for ρ and R given in Table XX.

TABLE XX.—*Mean Values of Diurnal Inequality Vectors.*

	ρ (unit 1 γ).			R (unit 1γ).		
	q.	*d.*	*d-q.*	*q.*	*d.*	*d-q.*
Whole 24 hours	12·4	22·7	14·9	13·3	31·9	24·3
Day...	17·2	26·2	14·8	18·4	35·0	23·5
Night	7·6	19·1	14·9	8·3	28·8	25·1

The difference between day and night in Table XX. is much less for disturbed than for quiet days; it practically vanishes in the case of the difference vector.

Figs. 8 and 13 and Tables XIX. and XX. refer to the year as a whole. The conclusions based on their study may require considerable modification in the case of individual months of the year.

CHAPTER VII

FOURIER COEFFICIENTS.

IN the case of mean diurnal inequalities based on hourly readings from a very large number of days, one may safely assert that the inequality can be represented by a finite number of terms of a Fourier series with such precision that the differences between the observed and calculated values are less than the instrumental uncertainties. The fact, however, that a certain mathematical operation is possible, by no means necessarily implies that it is desirable, or likely to be useful. If, for instance, the value of an element rose at a uniform rate from 6 a.m. to 6 p.m., and then fell at the same uniform rate from 6 p.m. to 6 a.m., one could indeed represent the progression by a Fourier series, but no information would be forthcoming from the series that would not be obtainable more simply from a consideration of the properties of the two straight lines forming the graphical representation of the phenomenon.

The utility of a Fourier expansion depends on several things. It is likely to be greater the more rapid the convergence of the series.

The fact that a diurnal inequality can be represented with a close approach to accuracy by the first four terms having periods of 24, 12, 8 and 6 hours respectively—as is usually true in Terrestrial Magnetism—does not necessarily imply that separate natural forces with these several periods are in operation. But if any distinct

natural force having one of these periods is in operation, the fact would largely enhance the probable usefulness of the Fourier expansion. If such a force exists, it is most likely to be detected by a comparison of the Fourier series obtained for different stations, and the most promising method of ascertaining its variation throughout the year is to study the annual variation of the Fourier coefficients. If there is any reason to suspect a connection between Terrestrial Magnetism and any meteorological or astronomical element, evidence for or against the connection is derivable from a study of the Fourier coefficients representing the diurnal variations in the two cases, and especially by considering the variation of these coefficients throughout the year.

At the present moment, our knowledge of regular meteorological variations is mainly confined to ground level, but it may one day be possible to infer the corresponding variations at higher levels, and the information we are now storing up for Terrestrial Magnetism may then shed a flood of light on the situation.

Even if there should be no natural force answering to each term of a Fourier expansion, a study of individual terms of the series may prove of marked utility. If we are comparing inequalities from different stations, or inequalities at different seasons of the year, the expansion in Fourier series enables us to indicate the nature of the differences that exist with a precision not otherwise attainable. Even if the Fourier expansion merely assists in demonstrating that two physical phenomena are not directly related, our labour will not have been thrown away.

The Fourier analysis of a diurnal inequality may be expressed in either of the equivalent forms:

$$a_1 \cos t + b_1 \sin t + a_2 \cos 2t + b_2 \sin 2t + \ldots ,$$
$$c_1 \sin (t + \alpha_1) + c_2 \sin (2t + \alpha_2) + \ldots\ldots ,$$

where a_1, b_1, c_1, α_1, etc., are known as *Fourier coefficients*,

while t denotes time counted from midnight, one hour in t counting as 15°.

The a, b constants are calculated directly from the twenty-four hourly values in the diurnal inequality, and the c (amplitude) and α (phase angle) coefficients are then deduced by means of the formulæ:

$$\alpha_n = \tan^{-1}(a_n/b_n),$$
$$c_n = a_n/\sin \alpha_n = b_n/\cos \alpha_n = \sqrt{a_n^2 + b_n^2},$$

where $n = 1, 2, 3$, etc.

An increased value of a phase angle means an earlier occurrence of the maxima and minima of the term involved, one hour of time answering to 15° in α_1, 30° in α_2, 45° in α_3, 60° in α_4, and so on.

The substitution of local mean time for G.M.T. makes no difference to the c constants, but alters the α constants. If we wish to replace a Fourier series in which t represents G.M.T. by one in which t denotes local mean time, at a station the west longitude of which is l, we increase α_1 by $l°$, α_2 by $2l°$, and so on. Kew, for instance, being 19′ west of Greenwich, if we replace G.M.T. by Kew mean time, we add 19′ to the value calculated for α_1.

If instead of local mean time we use local solar time, the correction which has to be applied to the phase angles is the same for all stations, but varies from month to month.

If one changes from G.M.T. to local solar time, one naturally combines the two corrections. Thus, at Kew, when G.M.T. is replaced by local solar time, the following corrections have to be applied to α_1—with twice as much to α_2, and so on:

	Jan.	Feb.	March.	April.	May.	June.
Correction .	+2° 42′	+3° 48′	+2° 28′	+0° 20′	−0° 33′	+0° 25′
	July.	Aug.	Sept.	Oct.	Nov.	Dec.
Correction .	+1° 41′	+1° 15′	−0° 58′	−3° 12′	−3° 20′	−0° 40′

In the case of diurnal inequalities derived from the whole year, from winter (November to February), equinox

(March, April, September, October) and summer (May to August), the necessary corrections to a_1 at Kew are respectively: $+0°\ 19'$, $+0°\ 37'$, $-0°\ 21'$ and $+0°\ 42'$.

While it is simple to correct the phase angles for any specified difference in the time used, it is important that in all cases the time employed should be explicitly stated.

Examples of how one determines the time of maximum in a Fourier term may make things clearer. As a first example, suppose the twenty-four-hour term to be $1'{\cdot}33 \sin(t+243°)$. A sine has its maximum when the argument is 90°, 450°, &c. Thus, for the maximum we put

$$t + 243° = 450°, \text{ whence } t = 207°.$$

Allowing 15° per hour, we have

$$t = 207/15 = 13{\cdot}8 \text{ hours, or } 1 \text{ h. } 48 \text{ m. p.m.}$$

The minimum occurs, of course, twelve hours earlier (or later), and so comes at 1 h. 48 m. a.m.

The term fluctuates between $+1'{\cdot}33$ and $-1'{\cdot}33$. Its so-called amplitude is $1'{\cdot}33$, but its range is double this, or $2'{\cdot}66$.

As a second example, suppose the twelve-hour term to be $0'{\cdot}84 \sin(2t+28°)$.

To get the first maximum we put

$$2t + 28° = 90°,$$

whence

$$t = 31° \equiv 2 \text{ h. } 4 \text{ m.}$$

Thus the first maximum $(+0'{\cdot}84)$ of the day occurs at 2 h. 4 m. a.m., a second equal maximum following, of course, at 2 h. 4 m. p.m. The two minima (each $-0'{\cdot}84$) occur midway between the maxima, and so at 8 h. 4 m. both a.m. and p.m.

Tables XXI. and XXII. give the amplitudes and phase angles of the twenty-four, twelve, eight, and six-hour terms in the mean monthly diurnal inequalities of D and

H at Kew (1890 to 1900), and Falmouth (1891–1902). The mean sunspot frequencies for the two periods, viz. 41·72 and 38·27, differ so little that the Kew (*K.*) and Falmouth (*F.*) data may be regarded as practically contemporaneous. Local mean time (L.M.T.) has been employed to bring out the parallelism between the phenomena. The unit employed in the amplitude coefficients in Table XXII. is 0·1γ.

TABLE XXI.—*Fourier Coefficients. Declination (Quiet Days) using L.M.T.*

Month.	c_1		c_2		c_3		c_4		a_1		a_2		a_3		a_4	
	K.	*F.*	*K.*	*F.*	*K.*	*F.*	*K.*	*F.*	*K.*	*F.*	*K.*	.	*K.*	*F.*	*K.*	*F.*
	′	′	′	′	′	′	′	′	°	°	°	°	°	°	°	°
January ...	1·33	1·20	0·84	0·95	0·47	0·50	0·27	0·29	243	245	28	31	248	246	63	62
February ...	1·78	1·69	1·01	1·05	0·59	0·60	0·27	0·29	234	236	32	34	234	233	39	40
March	2·34	2·15	2·00	1·97	1·23	1·24	0·52	0·53	225	225	38	38	223	224	48	48
April	2·75	2·55	2·39	2·35	1·36	1·34	0·38	0·39	214	211	39	36	225	223	59	56
May	3·07	2·81	2·61	2·45	1·10	1·04	0·17	0·16	217	211	56	50	248	246	78	81
June	3·42	3·09	2·45	2·41	0·86	0·86	0·05	0·08	208	206	48	46	245	246	72	67
July	3·21	2·96	2·39	2·38	0·92	0·94	0·20	0·13	211	208	50	45	231	232	-14	13
August ...	3·15	2·91	2·57	2·51	1·17	1·17	0·19	0·22	225	225	58	57	244	245	51	62
September ...	2·79	2·55	2·16	2·18	1·18	1·16	0·52	0·38	229	230	58	54	247	245	78	75
October ...	2·12	1·98	1·61	1·70	1·00	1·06	0·49	0·50	228	228	36	37	236	234	63	61
November ...	1·45	1·28	1·02	1·10	0·61	0·61	0·33	0·34	241	239	34	33	249	246	65	64
December ...	1·04	1·00	0·77	0·82	0·35	0·36	0·18	0·17	252	255	28	32	249	250	58	55
Arithmetic Means	2·37	2·18	1·82	1·82	0·90	0·91	0·30	0·29								

TABLE XXII.—*Fourier Coefficients. Horizontal Force (Quiet Days) using L.M.T.*

Month.	c_1		c_2		c_3		c_4		a_1		a_2		a_3		a_4	
	K.	*F*	*K.*	*F.*	*K.*	*F.*	*K.*	*F.*	*K.*	*F.*	*K.*	*F.*	*K.*	*F.*	*K.*	*F.*
	γ/10	γ/10	γ/10	γ/10	γ/10	γ/10	γ/10	γ/10	°	°	°	°	°	°	°	°
January ...	29	41	38	44	18	22	14	15	69	78	278	277	161	155	9	1
February ...	48	57	34	50	24	23	14	15	86	90	271	265	149	150	-11	-3
March ...	88	92	54	57	34	34	18	17	102	104	294	294	156	158	2	1
April	129	138	75	79	35	38	16	17	110	111	295	292	148	140	7	-4
May	151	161	61	67	19	18	13	9	129	130	315	310	201	188	63	69
June	149	159	62	63	23	21	7	5	134	131	313	309	207	203	29	55
July	149	156	67	68	22	21	6	7	131	127	312	308	181	177	12	19
August ..	146	153	61	62	32	30	15	15	127	126	327	324	204	205	37	43
September ...	126	132	58	57	40	39	23	22	122	120	333	327	199	199	32	37
October ...	100	112	58	62	33	33	18	18	101	101	295	292	163	165	17	18
November ...	55	66	53	58	21	23	12	13	93	100	286	283	157	161	24	19
December ...	16	24	31	39	10	11	6	7	63	95	269	265	146	164	1	2
Arithmetic Mean	99	108	54	59	26	26	13	13								

The last line in Tables XXI. and XXII. gives the arithmetic means of the twelve monthly values of the amplitudes. These means agree with the amplitudes in the mean diurnal inequality for the year only if the phase angles are invariable throughout the year, which is practically never the case. When the phase angle varies, as in the present instance, the arithmetic mean necessarily exceeds the amplitude in the mean diurnal inequality for the year. The contributions to the mean diurnal inequality for the year from the months most remote in phase neutralise one another to a greater or less extent. The arithmetic mean gives the better idea of the average amplitude throughout the year, provided the probable error in the amplitudes obtained for individual months be not excessive.

The fact that corresponding results at Kew and Falmouth are nearly identical is not *necessarily* a confirmation of their accuracy. If, however, either set of data were affected by considerable "accidental" errors of any kind, we should expect marked irregularities in the relationship of corresponding monthly values to one another. What we do find is an absence of such irregularities, which is simply extraordinary in view of the small amplitude of the terms of shortest period.

As regards amplitude, there is a small but systematic difference between the twenty-four-hour terms at the two stations. In every month the Kew D amplitude is the greater, the Kew H amplitude the less. The twelve-hour H term at Falmouth also exceeds the Kew value in all but one month, when the values at the two stations are nearly equal. In D the average values of c_2 at the two stations are identical, but the Falmouth value is slightly the larger in winter and the smaller in summer. The eight and six-hour terms in D and H have practically identical amplitudes at the two stations and vary in a similar fashion throughout the year.

The amplitude of the twenty-four-hour terms shows a maximum near midsummer, a minimum near midwinter. In the twelve-hour terms a double annual oscillation becomes recognisable, a secondary minimum appearing near midsummer. In the eight and six-hour terms the double annual oscillation is most marked, the maxima occurring near the equinoxes.

The phase angles for the two stations in Tables XXI. and XXII. show a remarkably close agreement, even in the case of a_4 where 1° represents only one minute of time. This emphasises the fact that while the character of the magnetic diurnal variation—unlike that of meteorological elements—is little if at all dependent on the purely local conditions, provided the station is undisturbed, it is the local time which determines the phase. This will be more clearly realised if it be remembered that if G.M.T. were substituted for local mean time, the Falmouth angles would be reduced relative to the Kew angles to the extent of 4°45′ in a_1 and over 19° in a_4.

In considering the agreement in the phase angles at the two stations, it should be remembered that the results are dependent on the same choice of days for the ten years common to the two periods dealt with. Thus "accidental" features, not of a local character, in any one month or year of the common period might sensibly influence the data in the tables, without creating any marked difference between Kew and Falmouth. Accidental features of this kind probably do exist, for instance, in the July values of a_4.

All the phase angles not affected by a minus sign are to be regarded as positive. Any minus angle can be made positive by adding 360° to it, but in the few instances where the minus sign appears it serves to bring out the relationship of the individual angle to other angles with which it would naturally be compared.

In most cases the phase angles show an annual variation

which is not accounted for by the difference between mean and solar time. Thus, taking an average from the two stations, the December and June values of the twenty-four-hour term phase angle in D differ by 46·5°, representing an earlier occurrence of the maximum in December by fully three hours.

The twelve monthly values of the amplitudes of each of the four terms dealt with in Tables XXI. and XXII. were expressed as percentages of their arithmetic mean, and a mean was taken of the D and H percentages for each month. The results appear in Table XXIII. for Kew (K) and Falmouth (F), and alongside for comparison appear the corresponding percentages derived from the monthly values of the amplitudes of the Fourier waves in the diurnal inequality of temperature. The temperature Fourier coefficients employed are those obtained for the period 1871–1882 by General Strachey,[1] who did not consider the six-hour wave. No V and I data were available for Falmouth, so D and H were alone considered.

TABLE XXIII.—*Amplitudes of Fourier "Waves" (Percentage Values). Annual Variation.*

Month.	24-hour term.				12-hour term.				8-hour term.				6-hour term.	
	D. & H.		Temp.		*D. & H.*		Temp.		*D. & H.*		Temp.		*D. & H.*	
	K.	*F.*	*K.*	*F.*	*K.*	*F.*	*K.*	*F.*	*K.*	*F.*	*K.*	*F.*	*K.*	*F.*
January ...	43	47	39	41	58	63	100	81	61	69	73	67	96	106
February ...	62	65	52	58	59	71	113	108	78	78	50	43	98	108
March	94	92	102	92	105	103	157	119	135	135	37	43	154	153
April	123	122	126	116	135	132	111	104	143	145	120	110	125	131
May	142	139	147	151	127	124	40	75	98	92	178	184	76	62
June	147	145	144	152	124	119	33	65	92	88	134	157	34	32
July	143	141	146	161	128	123	23	70	93	91	157	165	53	49
August	140	138	139	138	127	122	87	111	126	122	149	141	87	93
September ...	123	120	123	112	113	108	154	131	142	139	102	86	172	147
October ...	95	97	91	80	98	100	167	126	118	122	45	43	150	154
November ...	58	60	54	54	77	79	124	108	75	77	87	82	102	107
December ...	30	34	37	45	49	56	90	102	39	42	68	78	53	58

[1] *Phil. Trans*, 1893, *A*, Vol. 184, p. 644.

In the twenty-four-hour term the range of values and the character of the annual variation given in Table XXIII. is closely alike in magnetics and temperature. The chief difference is that in magnetics the December amplitude is markedly less than the January, whereas in temperature the December and January amplitudes are very similar. The minimum amplitude falls distinctly after the solstice for temperature, but not for magnetics. This fact, of course, is antagonistic to the view that temperature diurnal changes at ground level and magnetic diurnal changes are related in the way of cause and effect.

The twenty-four-hour wave is the only wave in which the annual variation follows a similar course in magnetics and temperature. The magnetic twelve-hour wave, as already pointed out, shows a *slight* depression or secondary minimum in its amplitude towards midsummer; but the double annual oscillation in the amplitude of the twelve-hour temperature wave is most conspicuous, and the midsummer minimum is the principal one. In fact, the annual variation of the twelve-hour temperature wave presents a considerable resemblance to that of the six-hour magnetic wave.

The phenomena in the eight-hour wave are exactly the opposite of those in the twelve-hour wave, inasmuch as it is the magnetic wave that shows a marked double annual oscillation, while the temperature wave does not.

The Kew and Falmouth temperature data in Table XXIII. differ more than do the magnetic data. This is especially true of the twelve-hour wave, the amplitude of which has a considerably greater annual variation at Kew than at Falmouth.

The amplitudes of the shorter period waves bear a much smaller ratio to that of the twenty-four-hour wave in the case of temperature than in the case of magnetics.

General Strachey's twenty-four, twelve, and eight-hour phase angles for temperature, when local time is used,

are larger for Kew than for Falmouth in every month of the year, except one in which the Falmouth eight-hour phase angle is the larger. This difference of phase, moreover, is not infinitesimal, but represents in the average month about fifty-six minutes of time in the case of the twenty-four-hour term. Finally, the range of the diurnal inequality of temperature is much less at Falmouth (a seaside station) than at Kew (an inland station); the amplitudes of the twenty-four-hour waves, for instance, at the two stations are roughly in the ratio of ten to nineteen. Thus, while there is a somewhat striking resemblance between the annual variations exhibited by the amplitudes of the twenty-four-hour Fourier waves in magnetics and temperature at both Kew and Falmouth, it is clear that temperature phenomena *near the earth's surface* in England are modified by local conditions in a degree to which there is no parallel in magnetics.

If the immediate cause of magnetic diurnal variation is thus not the diurnal variation of temperature at the earth's surface, still less can it be the diurnal variation of temperature in the earth's crust. For while there is, of course, a diurnal variation of temperature in the earth's superficial layers, its amplitude decays rapidly as the depth increases, and the shorter the period of the Fourier wave the more rapid its decay. Now, as we have seen, even at the surface the twenty-four-hour wave is a much larger fraction of the whole diurnal inequality in the case of temperature than in that of magnetics; thus the deeper one goes the more must the character of the temperature diurnal inequality depart from that of the magnetic diurnal inequality.

Barometric pressure and the potential gradient of atmospheric electricity are, next to temperature, the elements to which one would most naturally look for properties parallel to those exhibited by Terrestrial Magnetism. In the case, however, of both elements the amplitude of the

twenty-four-hour Fourier wave is largely dependent on local conditions, while its phase angle exhibits a much greater seasonal variation than is seen in magnetics at Kew and Falmouth.

Tables XXIV. and XXV. illustrate the influence of disturbance on the values of the Fourier coefficients for the Kew magnetic diurnal inequalities. The letters *q*, *o*, *d* indicate respectively quiet, ordinary, and disturbed days' inequalities.

Owing to the comparatively small number of disturbed days employed and to their nature, the Fourier coefficients based on them are affected by much greater uncertainties than are those for the quiet and ordinary days.

TABLE XXIV.—*Amplitudes of Fourier "Waves" in Seasonal Diurnal Inequalities.*

—		D (unit 1′).			I (unit 1′).		H (unit 0·1γ).		V (unit 0·1γ).	
		q.	o.	d.	q.	d.	q.	d.	q.	d.
c_1	Year	2·32	2·84	5·07	0·51	0·81	94	144	56	295
	Winter	1·39	1·93	4·36	0·24	0·78	36	29	25	211
	Equinox	2·48	3·10	5·70	0·60	0·81	110	113	62	243
	Summer	3·19	3·67	5·46	0·80	1·65	148	343	86	431
c_2	Year	1·79	1·76	1·76	0·25	0·62	51	123	42	90
	Winter	0·91	0·96	1·34	0·22	0·26	39	64	17	62
	Equinox	2·01	2·02	2·50	0·29	0·53	59	111	47	106
	Summer	2·50	2·37	1·71	0·32	1·11	62	204	65	104
c_3	Year	0·89	0·78	0·80	0·15	0·21	24	25	19	36
	Winter	0·50	0·45	0·44	0·10	0·11	18	24	9	26
	Equinox	1·17	1·05	0·63	0·21	0·27	33	34	25	34
	Summer	1·01	0·85	1·38	0·17	0·27	24	18	22	65
c_4	Year	0·28	0·29	0·50	0·09	0·13	13	16	6	8
	Winter	0·26	0·27	0·43	0·08	0·09	11	8	4	16
	Equinox	0·47	0·41	1·15	0·13	0·15	18	24	9	11
	Summer	0·12	0·11	0·64	0·07	0·15	10	17	5	17

Comparing the quiet and ordinary day *D* amplitudes in Table XXIV., one notices a remarkable difference between the twenty-four-hour wave and the others. The twenty-

four-hour wave has a markedly larger amplitude on ordinary than on quiet days at all seasons of the year, while the amplitudes of the twelve, eight, and six-hour waves are much the same for the two types of days. Thus the diurnal inequality of D departs more from a pure twenty-four-hour sine wave on quiet days than on others.

TABLE XXV.—*Phase Angles* of Fourier "Waves" in Seasonal Diurnal Inequalities.*

—	*D.*			*I.*		*H.*		*V.*	
	q.	*o.*	*d.*	*q.*	*d.*	*q.*	*d.*	*q.*	*d.*
	°	°	°	°	°	°	°	°	°
a_1 Year ...	223	230	258	295	263	117	137	124	191
a_1 Winter ...	241	248	272	250	193	83	12	154	193
a_1 Equinox ...	223	233	261	288	251	109	121	117	190
a_1 Summer ...	215	219	243	312	296	130	146	122	190
a_2 Year ...	45	42	12	132	141	302	309	275	277
a_2 Winter ...	30	27	−13	91	108	277	279	300	264
a_2 Equinox ...	42	41	31	135	151	303	311	272	272
a_2 Summer ...	52	50	4	155	143	316	316	272	289
a_3 Year ...	237	237	200	11	12	173	163	100	62
a_3 Winter ...	243	243	189	−17	−5	153	155	107	125
a_3 Equinox ...	231	231	186	3	−3	166	160	98	42
a_3 Summer ...	241	240	210	38	33	198	182	99	52
a_4 Year ...	56	57	105	210	228	18	42	285	264
a_4 Winter ...	55	54	66	193	196	5	15	279	198
a_4 Equinox ...	61	60	147	206	242	15	56	288	351
a_4 Summer ...	40	56	137	237	231	39	35	284	274

*The angles in this table relate to Greenwich and not to local mean time as in Table XXII. For the effect of replacing Greenwich by Kew mean time see p. 68.

The ordinary and quiet day D amplitudes vary fairly similarly with the season of the year. In both cases c_1 and c_2 have their largest values in summer, while c_3 and c_4 are largest at the equinoxes.

Contrasting quiet and disturbed day amplitudes, we see that in the case of the twenty-four and twelve-hour

terms the latter are usually markedly the larger; but this is not generally true of the eight and six-hour terms, except in the case of V. Even in V it is the twenty-four-hour term whose amplitude is most amplified during disturbance. The diurnal inequality on disturbed days thus makes a nearer approach to a pure sine wave of twenty-four-hour period than does the inequality on quiet days. Disturbed days thus differ from quiet days in the same direction that ordinary days do, but, if we may judge from what is seen in D, to an even greater extent.

Contrasting the quiet and ordinary day phase angles in Table XXV., we see no very decided difference except in the case of the twenty-four-hour term. In its case, however, there is a systematic difference, the angle being larger the whole year round—*i.e.*, the occurrence of the maximum earlier—on ordinary than on quiet days. In the average month the difference represents about half an hour, but it is less in summer than at other seasons. The twenty-four-hour D wave shows the same phenomenon on disturbed as on ordinary days, but to a considerably greater extent, the maximum in the case of the mean diurnal inequality for the year being about $2\frac{1}{3}$ hours earlier than on quiet days.

There seems the same general tendency in H and V as in D for the hour of occurrence of the maximum of the twenty-four-hour wave to be earlier on disturbed than on quiet days. In the case of the mean diurnal inequality for the year in V, the advance in time on disturbed days as compared to quiet days is about $4\frac{1}{2}$ hours.

In the case of D the first maximum seems distinctly earlier in the six-hour but later in the twelve and eight-hour waves on disturbed days than on ordinary or quiet days. In the other elements the differences between quiet and disturbed day phase angles are irregular and may be largely "accidental."

Some general conclusions follow from the facts disclosed.

The mean diurnal inequality for the equinoctial season usually approximates closely in range to that for the year, and it might thus appear sufficient to concentrate attention on the diurnal inequalities for summer and winter. Table XXIV. shows, however, that so far as the eight- and six-hour Fourier waves are concerned, equinox is not a half-way house between summer and winter, but is, in fact, the season when these waves have their largest development.

Differences between Fourier coefficients for days of different magnetic quality seem important in regard to theoretical explanations of the diurnal inequality.

If, for instance, we take Prof. Schuster's theory, theoretical expressions are deduced for the principal Fourier waves, and the main argument for or against the theory lies in the extent of their agreement with observation. We now know that the observational values from any station are likely to depend materially on the magnetic character of the days included. For a satisfactory comparison with any theory, we ought to have diurnal inequalities representing one definite state of matters on the earth.

Further, no theory can be regarded as complete, unless it is capable of accounting for the differences between the phenomena observed on quiet and disturbed days, as well as for the variations both in amplitude and in phase which the diurnal inequality displays at different seasons of the year.

In the meantime, the means of adequately checking a theory hardly exist, and until they do, the efforts of magneticians will probably be most usefully directed to extending and improving our knowledge of the phenomena.

CHAPTER VIII

ANNUAL VARIATION

THE annual variation in any element such as the range of a diurnal inequality can be represented by a Fourier series of which the successive terms possess the periods 12, 6, 4, &c. months. The different calendar months differ in length, and the central days of the twelve months do not divide the year into exactly equal intervals. Thus when we treat the mean monthly values as data answering to times separated by exactly the twelth part of a year, the values obtained for the Fourier coefficients are not absolutely correct. Further, when treating not one year but several, they are not all of one length, owing to the incidence of leap years. Still, the centre of most calendar months does not depart by more than twenty-four hours from the position it would have if each month were the twelth of the year. Thus while we might take subdivisions of the year more exactly equal than calendar months, or make a mathematical calculation of the errors involved in treating calendar months as equal, this does not seem worth while, at least when dealing with data from periods as short as eleven years.

In calculating the data given in Table XXVI., the departures of calendar months from the twelth part of the year were neglected. All the quantities relate to the diurnal inequality, including the range, the average departure from the mean, and the amplitudes of the 24-, 12-, 8-, and 6-hour Fourier waves.

The value of the quantity is supposed to be given in the form

$$M + P_1\sin(t+\theta_1) + P_2\sin(2t+\theta_2) + \ldots$$

where M is the arithmetic mean of the twelve monthly values, P_1 and P_2 the amplitudes and θ_1, θ_2 the phase angles of the 12-month (or annual) and 6-month (or semi-annual) terms. t denotes time calculated from the beginning of the year, treating one month as equivalent to 30°. P_1 and P_2 were usually calculated to one figure further than appears in the table, and these more exact values were employed in the calculation of P_1/M, P_2/M and P_2/P_1. In the case of P_1 and P_2 the unit is $1'$ in the case of declination and 1γ in the case of horizontal force. The character of the day is indicated by the letters q (quiet), o (ordinary) and d (disturbed) given in brackets after the letter D or H distinguishing the element.

TABLE XXVI.—*Annual Variation. Fourier Coefficients.*

Quantity.	Station.	P_1.	P_2.	θ_1.	θ_2.	P_1/M.	P_2/M.	P_2/P_1.
				°	°			
Range ... ... $D(q)$	Falmouth	3·51	1·26	275	277	0·44	0·16	0·36
,, ... ,,	Kew	3·81	1·22	275	273	0·47	0·15	0·32
,, ... $D(o)$	,,	3·36	0·94	279	280	0·40	0·11	0·28
Average departure $D(q)$	Falmouth	0·66	0·20	272	292	0·40	0·12	0·30
,, ,, ,,	Kew	0·73	0·21	274	291	0·42	0·12	0·28
,, ,, $D(o)$	,,	0·73	0·24	278	285	0·36	0·12	0·33
c_1 ... ... $D(q)$	Falmouth	0·99	0·18	274	306	0·45	0·08	0·18
c_1 ... ... ,,	Kew	1·09	0·17	274	304	0·45	0·07	0·16
c_1 ... ... $D(o)$	,,	1·05	0·25	276	300	0·36	0·09	0·24
c_1 ... ... $D(d)$	,,	1·05	0·76	319	228	0·20	0·14	0·72
c_2 ... ... $D(q)$	Falmouth	0·86	0·24	274	274	0·47	0·13	0·28
c_2 ... ... ,,	Kew	0·94	0·25	276	271	0·52	0·13	0·26
c_3 ... ... ,,	Falmouth	0·28	0·31	278	276	0·31	0·35	1·11
c_3 ... ... ,,	Kew	0·30	0·32	281	274	0·33	0·35	1·06
c_4 ... ... ,,	Falmouth	0·08	0·16	91	276	0·27	0·56	2·04
c_4 ... ... ,,	Kew	0·07	0·18	115	279	0·24	0·59	2·47
c_1 ... ... $H(q)$	Falmouth	6·56	1·40	268	254	0·61	0·13	0·21
c_1 ... ... ,,	Kew	6·65	1·47	269	261	0·67	0·15	0·22
c_2 ... ... ,,	Falmouth	1·11	0·71	281	239	0·19	0·12	0·64
c_2 ... ... ,,	Kew	1·47	0·78	270	241	0·27	0·14	0·53
c_3 ... ... ,,	Falmouth	0·23	1·15	244	291	0·09	0·44	5·08
c_3 ... ... ,,	Kew	0·39	1·05	241	290	0·15	0·41	2·69
c_4 ... ... ,,	Falmouth	0·24	0·62	119	292	0·18	0·46	2·62
c_4 ... ... ,,	Kew	0·12	0·64	126	285	0·09	0·47	5·25

Any departure from mathematical precision in disregarding the differences between the lengths of months applies equally to all the cases dealt with, and so cannot well introduce differences between phase angles in terms having the same period.

Even if substantial differences had presented themselves between corresponding results at Kew and Falmouth, they could not with certainty have been ascribed to defects in the observational data, owing to the distance between the stations. And conversely, the remarkable similarity that actually does present itself between the results for the two places in Table XXVI. cannot serve as an absolute demonstration of high accuracy. It will probably, however, be generally conceded that it at least creates a strong presumption that the accuracy attained is highly satisfactory.

We cannot expect two terms of a Fourier series to represent the observed annual variation exactly, but in the present case the terms with periods shorter than 6 months appear to be small. Values calculated for individual months from the series given by Table XXVI., and from the corresponding series for V and I from quiet days at Kew, were compared with the observed values. Taking an average from the four elements D, I, H, and V, the mean difference between observed and calculated values, expressed as a percentage of the mean value of the quantity for the year, was 4 for the range and the average departure from the mean, 5 for c_1, 7 for c_2, 7·5 for c_3, and 14 for c_4.

In the case of c_4, the semi-annual term considerably exceeds the annual term, so a considerable contribution from terms with periods shorter than 6 months is probable *a priori*.

Omitting the disturbed day results in Table XXVI., we see but little variation in the values for θ_2, and the same is true of θ_1 except in the case of c_4. Constancy of value

in either angle means fixity of date for the maximum value of the element. There is thus a marked tendency for the maxima, whether in the 24 or the 12-hour term, to fall about one season of the year. The values of θ_1 and θ_2 obtained for V and I at Kew are, it may be added, generally very similar to those given for D and H.

Generally speaking, the ratio P_2/P_1 borne by the amplitude of the 6-month to that of the 12-month term increases as we pass from c_1 to c_2, from c_2 to c_3, and from c_3 to c_4. This is as true of I and V at Kew as of D and H.

In the case of Kew declination there is a reduction in P_1/M as we pass from quiet to ordinary and from ordinary to disturbed days. There is also on disturbed days a rise in P_2/M alongside the fall in P_1/M, so that the importance of the semi-annual term relative to the annual term is much enhanced.

An increased value of a phase angle means an earlier occurrence of the maximum, 1° in θ_1 or 2° in θ_2 answering roughly to one day. Comparing the values of θ_1 for declination from quiet and ordinary days, we see that the latter are always the larger. Taking an average from the range, the average departure from the mean and c_1, the maximum in the annual term occurs about three days earlier for ordinary than for quiet days. There is a further advance in the case of disturbed days.

Table XXVII., showing the actual dates of occurrence of the maxima of the annual term and of the earliest maxima of the semi-annual term, from quiet day results at Kew and Falmouth, will bring out even more clearly the remarkable accordance between the phase angles calculated for the two stations, as well as their real significance.

Except in the case of c_4, the annual term has its maximum near midsummer and its minimum near midwinter. In the case of c_4, except in V, the phase is inverted, the maximum appearing near midwinter. The

semi-annual term in all the cases in the table has its maxima near the equinoxes, with minima near midwinter and midsummer.

TABLE XXVII.—*Dates of Maxima in Annual and Semi-annual Terms (Quiet Days).*

—	*D.*		*I.*	*H.*		*V.*
	Kew.	Falmouth.	Kew.	Kew.	Falmouth.	Kew.
Annual term :—						
Ranges	June 26	June 27	July 8	July 3	July 3	June 19
Average departure	,, 27	,, 29	,, 8	,, 3	,, 3	,, 20
c_1	,, 27	,, 28	,, 6	,, 3	,, 4	,, 22
c_2	,, 25	,, 28	,, 18	,, 2	June 20	,, 20
c_3	,, 20	,, 23	,, 21	,, 31	July 28	,, 17
c_4	Dec. 6	Dec. 30	Nov. 5	Nov. 25	Dec. 2	May 29
Semi-annual term :—						
Ranges	Mar. 30	Mar. 29	April 1	April 6	April 6	April 16
Average departure	,, 21	,, 21	,, 4	,, 8	,, 15	,, 10
c_1	,, 15	,, 14	,, 3	,, 6	,, 10	,, 26
c_2	April 1	,, 31	,, 26	,, 16	,, 18	,, 13
c_3	Mar. 30	,, 29	Mar. 20	Mar. 22	Mar. 22	Mar. 29
c_4	,, 27	,, 29	,, 24	,, 24	,, 21	April 7

CHAPTER IX

ABSOLUTE DAILY RANGE

By *absolute* daily range is here meant the excess of the absolutely largest value during the twenty-four hours over the absolutely smallest value, irrespective of the times at which these extreme values occur. In an element which requires a temperature correction, it may occasionally happen that the temperature corrections to curve ordinates which are nearly equal alter their order of magnitude when expressed as true force. Thus the determination of the maximum and minimum is simpler to carry out for D than for H or V, unless there is absolute temperature compensation, or else no sensible diurnal variation of temperature in the magnetograph room.

Sometimes, through rapid loss of magnetism of the magnet or other cause, there is a sensible daily drift in curves of a force magnetograph, and this, it is needless to say, may prove an obstacle in the way of exact determination of maxima and minima.

The mean absolute daily range for a month or season necessarily exceeds the range of the corresponding mean diurnal inequality, unless the maxima and minima throughout the whole period occur at fixed times coincident with exact hours, and the excess of the mean absolute range over the corresponding inequality range is often very considerable.

Two stations may have equal inequality ranges and yet differ notably in the mean energy of the magnetic forces.

A lesser general activity may be compensated by a greater uniformity in the times of the daily maximum and minimum. Thus a study of absolute ranges is a useful auxiliary to the study of the regular diurnal inequality.

Table XXVIII. contrasts the mean monthly values of the absolute declination ranges derived from quiet (q), ordinary (o), and all (a) days at Kew with the corresponding inequality ranges from quiet and from ordinary days. The data are all derived from the eleven-year period 1890 to 1900. The inequality ranges in this instance are arithmetic means from the eleven months of the same name treated separately, and thus differ somewhat from the ranges in Tables XIII. and XIV., which are derived from inequalities embracing the eleven months of the same name.

TABLE XXVIII.—*Inequality and Absolute Declination Ranges at Kew.*

Month.	Inequality Range.		Absolute Range.			Monthly values as percentages.				
						Inequality Range.		Absolute Range.		
	q.	*o.*	*q.*	*o.*	*a.*	*q.*	*o.*	*q.*	*o.*	*a.*
January	4′·4	5′·1	6′	10′·1	11′·2	54	59	64	81	82
February ...	5·2	6·3	7·6	11·9	13·7	63	74	79	94	101
March	9·0	9·1	10·6	14·2	15·9	110	107	110	113	117
April	10·7	10·9	11·8	14·2	15·0	130	129	123	113	111
May	11·1	10·7	12·1	13·8	14·9	135	126	126	110	110
June	10·7	10·9	11·9	13·3	13·7	131	128	124	105	101
July	10·5	10·7	11·6	13·5	14·1	128	125	121	107	104
August	11·0	11·0	11·9	13·7	14·2	134	129	124	109	105
September ...	9·8	9·6	10·9	13·7	14·6	120	113	113	109	107
October	7·6	7·8	9·2	13·1	14·1	93	92	95	104	104
November ...	4·9	5·5	6·5	10·4	11·7	60	64	68	83	86
December ...	3·6	4·6	5·1	9·0	9·8	43	54	53	72	72
Arithmetic Means...	8·2	8·5	9·6	12·6	13·6					

Table XXVIII. also expresses both species of ranges as percentages of their mean, to bring out more clearly the differences in the character of the annual variation. In

calculating the percentage figures, use was made of ranges going to 0′·01.

On quiet days, taking the year as a whole, the absolute range is some 17 per cent. larger than the inequality range, but the excess varies from 8 per cent. in August to 43 per cent. in December.

On ordinary days, taking means from the twelve months, the absolute range is almost 50 per cent. in excess of the inequality range, the excess varying from about 20 per cent. in June to about 100 per cent. in January.

All days—meaning thereby the ordinary together with the 209 highly disturbed days—have naturally the largest absolute range of all. The difference between all and ordinary day absolute ranges is largest in winter. The mean absolute range derived from all December days of the eleven years is no less than 2·75 times the inequality range for the quiet days of that month. But in June the mean absolute range from all days is only 1·3 times the inequality range from the quiet days.

The anticipations of the man who regards the inequality range as the range to be expected on individual days will usually be seriously in error in winter, and seldom very exact even in summer.

Considering the percentage figures in Table XXVIII., as we pass from left to right, we see the midwinter figures go up, and the midsummer figures go down. Disturbance thus tends to bring winter and summer closer together. While the inequality ranges give only a suggestion of a secondary minimum in midsummer, the absolute ranges from ordinary days and still more those from all days show a marked midsummer depression, while the maxima near the equinoxes — especially the spring equinox — are conspicuous.

The annual variation of absolute ranges may be represented, like that of the inequality ranges, by Fourier series with periods of twelve months and its submultiples.

Using the same terminology as in Table XXVI., we have the results given in Table XXIX.

TABLE XXIX.—*Annual Variation of Absolute Declination Ranges at Kew. Fourier Coefficients.*

—	P_1.	P_2.	θ_1.	θ_2.	P_1/M.	P_2/M.	P_2/P_1.
	′	′	°	°			
Quiet days ...	3·34	1·14	280	282	0·35	0·12	0·34
Ordinary days .	2·15	1·40	281	285	0·17	0·11	0·65
All days	1·67	1·64	295	287	0·12	0·12	0·98

If we contrast the quiet day results in Table XXIX. with the corresponding results for inequality ranges in Table XXVI., we find a reduction in both P_1 and P_2, but P_2/P_1 is slightly larger for the absolute range than for the inequality range. The values of θ_1 and θ_2 for the absolute range exceed those for the inequality range by 5° and 9° respectively, representing an advance of some five days in the times of the maxima.

In the case of ordinary days, while P_1 is less for the absolute than the inequality range, the contrary is true of P_2; and P_2/P_1 is fully twice as big for the former range as the latter. The phase angles are again greater for the absolute range, θ_1 by 2° and θ_2 by 5°, representing in each case an advance of about two days in the date of the maxima.

The changes seen in passing from inequality to absolute ranges are further developed as we pass from absolute ranges on ordinary days to those on all days. P_1 again falls, while P_2/P_1 rises to nearly unity. The phase angles, especially that of the annual term, are also increased.

The differences between absolute and inequality ranges of declination which have been described for Kew seem to exist at all stations to a greater or less extent. An example is afforded by data for Pavlovsk given in Table XXX. The data, which are derived from the annual Pavlovsk tables, are means for the eleven years

1890 to 1900. The letters "I" and "A" denote respectively the inequality and absolute ranges.

TABLE XXX.—*Pavlovsk Inequality and Absolute Declination Ranges.*

Month.	Jan.	Feb.	March.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
	′	′	′	′	′	′	′	′	′	′	′	′
"I" Range	4·9	6·2	8·6	10·9	12·2	12·3	11·8	11·4	8·7	6·9	5·5	4·6
"A" ,,	13·4	17·2	18·2	17·3	17·8	15·9	16·9	16·6	16·8	15·7	13·9	12·4

The values assigned to the "I" ranges in Table XXX. are, as already stated, arithmetic means of the values assigned to eleven individual years. Such a mean is usually slightly larger than the range obtained by combining all the days of the given month for all the years taken together, because there is usually some slight variation in the hours of maximum and minimum as we pass from one year to another. If we had combined all the days of the eleven years we should have obtained for the "I" ranges values probably a few per cent. smaller than those in Table XXX.

The annual variation in the "A" ranges at Pavlovsk is less smooth than the corresponding variation at Kew in Table XXVIII. Still the general features at the two stations are closely alike.

Table XXXI aims at supplementing our knowledge of the mean values of absolute declination ranges at Kew by some information as to their degree of variability. It is based on the 4017 days of the eleven years 1890 to 1900, and shows for each month of the year the number of occasions on which the absolute daily range lay within the limits given at the heads of the columns. For instance, there were only 188 days in all on which the range was less than 5′. Of these days 64 were in December, 51 in January, 42 in November, 26 in February, 3 in October and 1 each in March and September.

TABLE XXXI.—*Absolute Declination Ranges at Kew. Frequency of Occurrence.*

Month.	Absolute Ranges.				Number of Occurrences in 11 years.				
	0′ to 5′	5′ to 10′	10′ to 15′	15′ to 20′	20′ to 25′	25′ to 30′	30′ to 35′	35′ to 40′	over 40′
January	51	145	69	37	24	7	4	3	1
February	26	99	84	51	26	10	4	2	8
March...	1	72	138	61	32	21	8	1	7
April	0	43	167	73	27	10	6	3	1
May	0	57	157	85	20	12	3	0	7
June	0	56	185	67	15	1	3	1	2
July	0	59	185	70	14	5	2	2	4
August	0	37	202	75	22	1	2	0	2
September... ...	1	68	153	71	19	5	4	5	4
October	3	103	111	67	34	10	11	2	0
November	42	140	81	28	14	9	8	5	3
December	64	166	56	29	14	7	1	1	3
Year	188	1045	1588	714	261	98	56	25	42
Winter	183	550	290	145	78	33	17	11	15
Equinox ...	5	286	569	272	112	46	29	11	12
Summer	0	209	729	297	71	19	10	3	15

Ranges under 10′ are most common in winter and least common in summer. Ranges from 10′ to 20′ are most common in summer and least common in winter. Ranges from 20′ to 35′ are most common in the equinoctial months, and more common in winter than in summer. Of ranges above 35′ the whole number was so small that a much longer series of years would be required to justify a final statement as to their normal annual distribution. The range exceeded 20′ on 482 days, or almost exactly 12 per cent. of the total; but in June this percentage was only 7, whereas in March it was 20. At Kew, summer is obviously the season when magnetic conditions are most uniform. This greater homogeneity contributes in no small degree to the difference apparent between the ranges of the diurnal inequalities in summer and winter.

Table XXXII. deals with the variability in the times of occurrence of the daily maximum (extreme westerly position), and minimum (extreme easterly position) of declination at Kew. Like Table XXXI. it is based on the eleven years

1890—1900, but a few days had to be omitted, especially in the case of the maxima, owing to some uncertainty as to the exact hours of occurrence of the extreme values. The figures represent the number of days on which the maximum or minimum, as the case may be, occurred during the hour indicated in the first column. The times of occurrence were really measured to the nearest minute. As in previous tables, the three seasons are each composed of four months.

TABLE XXXII.—*Occurrences of Declination Maxima and Minima at Kew.*

Hour ending	Maxima.			Minima.			Year.	
	Winter.	Equinox.	Summer.	Winter.	Equinox.	Summer.	Maxima.	Minima.
1	8	5	4	189	98	51	17	338
2	7	2	6	56	48	38	15	142
3	14	5	4	35	36	28	23	99
4	12	4	2	23	35	26	18	84
5	6	5	4	16	16	24	15	56
6	8	5	6	17	18	138	19	173
7	12	10	4	5	39	333	26	377
8	7	2	0	15	155	384	9	554
9	6	1	2	77	287	143	9	507
10	5	4	1	46	45	10	10	101
11	14	4	0	1	1	0	18	2
Noon	75	40	43	0	0	0	158	0
1	476	456	361	0	0	0	1,293	0
2	432	639	568	0	0	0	1,639	0
3	121	117	281	4	0	0	519	4
4	26	24	46	5	1	0	96	6
5	23	3	8	29	4	0	34	33
6	20	2	6	25	38	2	28	65
7	18	2	0	55	60	10	20	125
8	2	1	1	107	84	20	4	211
9	2	2	1	139	105	29	5	273
10	3	1	1	164	95	24	5	283
11	0	2	2	154	78	40	4	272
12	4	2	1	159	95	49	7	303
Totals	1,301	1,338	1,352	1,321	1,338	1,349	3,991	4,008

Taking the year as a whole, 86 per cent. of the days have the maximum occurring between noon and 3 p.m., and in the equinoctial months this percentage rises to 90. On the other hand, there are only twenty-five days—or about

0·6 per cent. of the total—on which the maximum presents itself during the five hours ending at midnight. There is a slight suggestion in all three seasons, especially winter, of a small secondary maximum frequency of occurrence of the maxima in the early morning.

As regards the minima, the seasons agree in showing a complete absence of occurrences between 11 a.m. and 2 p.m., covering the time of most frequent occurrence of maxima. In summer no minimum was observed between 10 a.m. and 5 p.m. The law of occurrence of minima shows much greater variability with the season of the year than does the law of occurrence of maxima. In summer there is a conspicuous maximum frequency of occurrence from 6 to 8 a.m. There is also a secondary maximum of frequency near midnight, but relatively it is very insignificant. In equinox the greatest frequency of occurrence is still very decidedly in the forenoon—about an hour later than in summer—but occurrences during the night become much less infrequent. In winter there is still a maximum of frequency of occurrence in the forenoon—again a little later than in equinox—but the *principal* maximum of frequency is now near midnight. In both winter and equinox the frequency of occurrence of the minima is represented rather by a high plateau extending from 8 p.m. to 1 a.m. than by a range with one conspicuous summit.

CHAPTER X

ANTARCTIC MAGNETIC RESULTS

THE National Antarctic Expedition of 1901–4 had a set of Eschenhagen magnetographs, which were in operation at the Winter Quarters of the Expedition for nearly two years, under the immediate supervision of the physicist, Mr. L. C. Bernacchi. The magnetic curves were measured by Mr. Bernacchi and members of the Kew staff, and the results were discussed by the present writer. The phenomena were of so distinctive a character as to call for a special chapter.

The most striking feature was the incessant occurrence and the large size of disturbances. The magnetograph as set up at Winter Quarters was unfortunately too sensitive for so highly disturbed a station, and there was consequently a considerable loss of trace, more especially of *H*. In the Eschenhagen instrument, *D*, *H*, and *V* are recorded on one sheet, as well as a trace from a metallic thermometer adjacent to the vertical force magnet. There are also three base line traces, one serving for both temperature and vertical force. At times of large disturbance the traces from the different elements are apt to cross, and confusion may result. The vertical force magnetograph was not highly sensitive, and very little *V* trace was lost through the limits of registration being exceeded; but the instrument had a large temperature coefficient, and when the temperature trace went off the

sheet—a not infrequent event during some months—no satisfactory use could be made of the vertical force trace.

Winter Quarters lies some 400 miles south-east of the magnetic pole, and consequently the north pole of a magnet there points nearer south than north. In the figure, if *NS* and *WE* represent the geographical meridian and the west-east line at Winter Quarters, and *nOs* the position of the compass needle, then the average value of the angle *nON* was about 152° 40′.

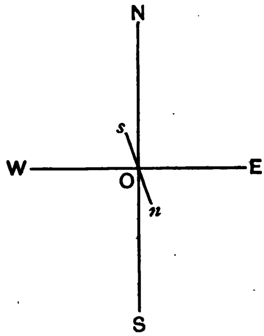


Fig. 14.

By an increase of declination is here meant an increase in the angle *nON*. The south pole of the magnet dipped, of course, and by an increase in *V* is meant the increase in the force pulling the south pole of the magnet downwards, or the north pole towards the zenith.

Diurnal inequalities were calculated for each month, and for the twelve months of the year from the years 1902 and 1903 combined, local mean time being used in all cases. The sun being below the horizon during the whole of May, June, and July, an inequality was derived for the season — termed midwinter—composed of these three months. Similarly an inequality was derived for the season—termed midsummer—composed of November, December, and January, during which the sun was continually above the horizon.

In the case of *D* a selection was made of the days of least disturbance, and diurnal inequalities were found for these separately, as well as for all the days of complete registration. These "quieter" days numbered 220, out of a total of 426 which were utilised for the all day *D* inequality. The term "quieter" is purely relative. Not one single day would have been considered

a quiet day at Kew. The midwinter and midsummer diurnal inequalities for D, I, H, and V are given side by side in Table XXXIII. under the respective headings W and S, and are illustrated by Fig. 15. The table contains quieter as well as all day results for D, but the figure shows the latter only. Even the seasonal data in Table XXXIII. present slight irregularities, but they are immensely smoother than had been anticipated beforehand from the general appearance of the curves.

TABLE XXXIII.—*Antarctic Diurnal Inequalities.*

Hour.	Declination.				Inclination.		Horizontal Force. (Unit 1γ.)		Vertical Force. (Unit 1γ.)	
	All Days.		Quieter Days.							
	W.	*S.*	*W.*	*S.*	*W.*	*S.*	*W.*	*S.*	*W.*	*S.*
	′	′	′	′	′	′				
1	0·0	− 4·8	+0·5	− 4·6	+0·46	+0·80	− 8·9	−15·2	+7	+19
2	+ 1·4	+ 2·8	+1·2	+ 0·4	+0·44	+1·08	− 8·7	−20·8	+5	+22
3	+ 3·4	+ 5·2	+1·8	+ 5·0	+0·47	+1·18	− 9·6	−23·0	+3	+20
4	+ 6·6	+13·7	+2·7	+ 9·6	+0·48	+1·26	− 9·9	−24·9	+1	+18
5	+ 8·2	+14·9	+4·4	+12·4	+0·47	+1·33	− 9·8	−27·1	−1	+10
6	+ 9·2	+20·7	+5·1	+21·0	+0·36	+1·02	− 7·7	−21·0	−3	+ 5
7	+10·2	+22·7	+6·2	+27·7	+0·27	+0·85	− 6·0	−17·8	−4	+ 8
8	+10·7	+33·2	+6·1	+33·4	+0·13	+0·76	− 3·2	−15·6	−6	+ 7
9	+11·3	+35·3	+6·4	+36·4	−0·03	+0·50	0·0	−11·1	−8	− 7
10	+11·6	+30·4	+5·8	+28·9	−0·18	+0·03	+ 3·0	− 2·6	−8	−22
11	+10·3	+17·5	+4·5	+12·4	−0·31	−0·41	+ 5·8	+ 6·0	−9	−31
Noon	+ 7·8	+10·0	+3·2	+ 5·1	−0·49	−0·95	+ 9·4	+16·9	−9	−36
1	+ 3·8	+ 3·1	+1·1	− 1·8	−0·66	−1·34	+13·0	+25·5	−9	−31
2	+ 0·9	− 4·9	−0·5	−11·6	−0·71	−1·54	+14·2	+30·2	−6	−23
3	− 3·8	−15·8	−2·3	−18·4	−0·75	−1·44	+15·3	+28·8	−5	−18
4	− 9·1	−22·2	−4·6	−21·8	−0·65	−1·47	+13·5	+29·9	−2	−11
5	−11·8	−25·8	−6·4	−22·4	−0·53	−1·24	+11·3	+25·9	+2	− 3
6	−15·1	−27·6	−7·6	−22·6	−0·34	−0·95	+ 7·5	+20·2	+5	+ 3
7	−15·2	−28·8	−7·0	−25·8	−0·13	−0·54	+ 3·2	+11·7	+6	+ 6
8	−14·5	−25·0	−7·6	−22·7	+0·10	−0·23	− 1·3	+ 5·3	+8	+ 7
9	−11·1	−21·6	−6·1	−15·1	+0·31	−0·07	− 5·8	+ 2·3	+9	+10
10	− 8·6	−15·5	−4·2	−11·2	+0·40	+0·21	− 7·7	− 3·2	+9	+14
11	− 4·1	−13·3	−2·1	− 8·7	+0·45	+0·42	− 8·7	− 7·5	+8	+15
12	− 1·7	− 4·2	−0·3	− 5·1	+0·47	+0·72	− 9·2	−13·5	+7	+18
Range	26·8	64·1	14·0	62·2	1·23	2·87	25·2	57·3	18	58
Average Departure	7·9	17·5	4·1	16·0	0·40	0·85	8·0	16·9	5·8	15·2

The D ranges in Table XXXIII. are large from whatever point of view they are regarded. At the same time the fact should be borne in mind that the force perpendicular to the magnetic meridian required to

produce a small change ΔD in D is given by $H\Delta D$, and so for a given value of ΔD diminishes as H diminishes. At Winter Quarters H was only about 0·065 as compared with 0·185 at Kew, thus the force required to produce a change of 1′ in D is only about 1·9γ at the former station, as compared with 5·3γ at the latter. If H at Winter Quarters had been as large as at Kew the D range would have been less than it actually was in the ratio 36:100.

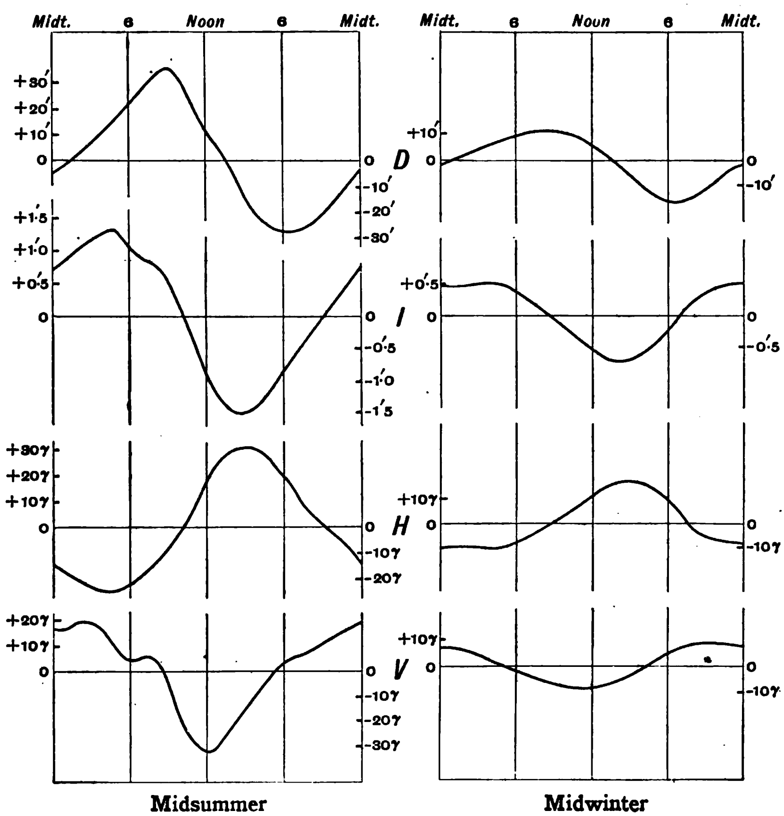


FIG. 15.—ANTARCTIC DIURNAL INEQUALITIES.

It is readily seen from Table XXXIII. and Fig. 15 that the midwinter and midsummer inequalities are remarkably alike in type, considerably more alike than at Kew,

for instance. A close resemblance in type, it may be added, persisted throughout the whole year. The ratio borne by the range to the average departure from the mean is less at midwinter than at midsummer for all the elements, and even at midsummer it is unusually small, *i.e.* the curve illustrating the diurnal variation is unusually rounded.

Another remarkable feature is the activity of the forces producing the inequality during the "night" hours. The absence in the Antarctic inequalities of the marked distinction usually visible between day and night is perhaps not very surprising in the continuous day of midsummer and the continuous night of midwinter, but it is equally true of the equinoctial months. The inequalities at all seasons, as we shall see more clearly presently, show an exceptionally close approach to pure sine waves of twenty-four hour period.

An interesting feature is the close agreement of the ranges of the quieter and the all day D inequalities in midsummer, in contrast with the large difference between them in midwinter. This is the more surprising when it is remembered that the quieter days are included in the all days and make up about half their number. The natural inference is that the presence of disturbance produces, when the sun is below the horizon, conditions which are otherwise secured when the sun is above the horizon. The enormous reduction seen in the D range in midwinter as we pass from all days to quieter days suggests that if really quiet days ever exist in the Antarctic at this season the inequality range during them must be very small indeed.

There is a curious undulation in the midsummer V curve in Fig. 15 between 4 a.m. and 8 a.m.—slightly indicated also in the equinoctial curve, which is not reproduced here—as to the truly representative character of which some doubt may be entertained. The hours of

the day during which it occurs were remarkable for the number and amplitude of oscillatory movements, and the days on which the midsummer inequality is based numbered only forty-one; thus the phenomenon may be "accidental."

Table XXXIV. gives the mean diurnal inequalities for the year in *D*, *I*, *H*, and *V*, and also in the south and west components. Maxima and minima are in heavy type. The ranges of the inequalities and the average departures from the mean are given at the foot.

TABLE XXXIV.—*Antarctic. Mean Diurnal Inequality for the Year.*

Hour.	Declination. All days.	Declination. Quieter days.	Inclination.	Horizontal Force (Unit 1γ).	Vertical Force (Unit 1γ).	South Component (Unit 1γ).	West Component (Unit 1γ).
	′	′	′				
1	−2·0	−**0·9**	+0·61	−11·7	+**13**	−12·2	+2·0
2	+2·1	+1·8	+0·68	−13·0	+12	−9·9	+9·6
3	+5·2	+4·5	+0·71	−13·9	+10	−7·9	+15·2
4	+9·4	+6·8	+**0·73**	−14·6	+8	−4·7	+22·7
5	+12·2	+9·0	+**0·73**	−**14·9**	+3	−2·6	+27·6
6	+15·3	+11·7	+0·55	−11·5	0	+3·2	+31·3
7	+17·2	+15·0	+0·42	−8·7	0	+7·3	+33·2
8	+21·5	+17·3	+0·32	−6·8	−2	+12·8	+39·6
9	+**23·5**	+**18·1**	+0·10	−2·5	−6	+18·3	+**41·2**
10	+21·2	+15·8	−0·18	+2·6	−13	+**21·0**	+34·8
11	+15·3	+9·2	−0·43	+7·4	−17	+20·1	+22·6
Noon	+9·8	+4·9	−0·68	+12·4	−**20**	+19·6	+11·0
1	+3·2	+0·1	−0·93	+17·7	−20	+18·6	−2·7
2	−3·8	−5·9	−**1·01**	+**19·6**	−16	+14·1	−15·5
3	−11·1	−9·5	−0·97	+19·2	−12	+7·3	−27·7
4	−16·6	−12·9	−0·90	+18·3	−6	+1·8	−36·7
5	−19·9	−14·6	−0·74	+15·4	−1	−3·8	−40·9
6	−**22·0**	−15·5	−0·53	+11·5	+3	−9·2	−**42·7**
7	−**22·0**	−**15·9**	−0·21	+5·0	+6	−14·9	−39·7
8	−19·9	−14·6	+0·04	0·0	+9	−17·3	−33·8
9	−16·0	−10·6	+0·24	−4·0	+11	−**17·6**	−25·4
10	−11·6	−7·2	+0·37	−6·7	+12	−16·1	−16·7
11	−7·6	−4·2	+0·51	−9·6	+12	−15·2	−8·5
12	−3·3	−1·9	+0·60	−11·2	+**13**	−13·0	−0·4
Range... ...	45·5	34·0	1·74	34·5	33	38·6	83·9
Average departure	13·0	9·5	0·55	10·8	9·4	12·0	24·2

There was much more frequent loss of the *H* trace than of the *D* or *V* traces, and the loss naturally occurred

most often on days of large range. All days of incomplete trace were omitted when deriving the diurnal inequality, and it is thus not improbable that the range given for H in Table XXXIV. is smaller than it would have been if all the days utilised for the D or V inequalities had been available.

Fig. 16 gives WS, WV, and SV vector diagrams for the mean diurnal inequality for the year. The horizontal plane diagram is much more symmetrical in shape than that for Kew (Fig. 8). The area traced by the vector during the night (*i.e.* from hours 18 to 6) is not conspicuously less than that traced during the day.

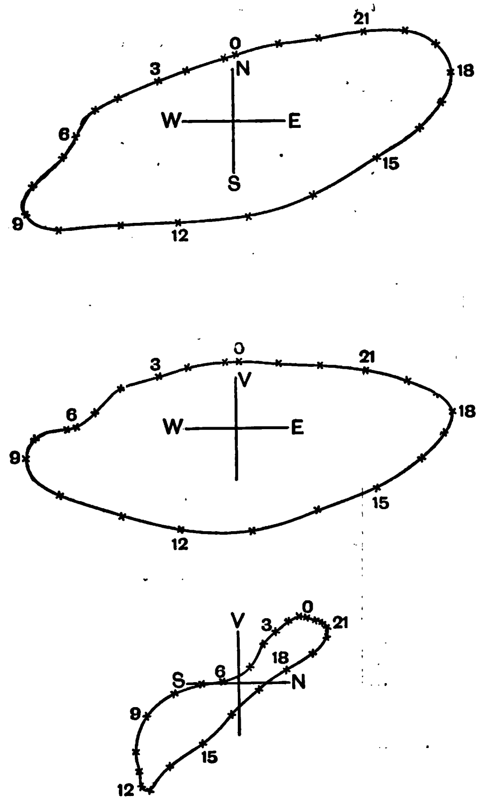


FIG. 16.—ANTARCTIC VECTOR DIAGRAMS.

The WV diagram—the vertical force on the north pole of the magnet is *upwards*—is also of a very symmetrical type, resembling an ellipse with its major axis slightly inclined to the horizontal.

The VS diagram, though less symmetrical than the other two, is yet notably more symmetrical—as between day and night—than the corresponding diagram for quiet days at Kew. It presents the feature discovered by

Mr. Sangster, *viz.*, a nearly rectilinear course in the early afternoon. In the Antarctic this rectilinear portion may be regarded as extending from 1 p.m. to 6 p.m. Its average direction during this interval makes with the horizon the angle 39°·6. Winter Quarters being in latitude 77°51′ S., it follows that the rectilinear portion of the diagram is inclined to the earth's axis of rotation at about 62°½. The departure from perpendicularity is thus in this instance considerable.

Table XXXV. gives the ranges of the *D*, *I*, *H*, and *V* diurnal inequalities for each month of the year. The irregularities are presumably due to the fact that less than two years' observations were available. The existence of a prominent maximum in midsummer and a minimum in midwinter seems clear. Ranges in the equinoctial months fall conspicuously short of those in midsummer.

TABLE XXXV.—*Antarctic Diurnal Inequality Ranges.*

Month.	Declination.		Inclination.	Horizontal Force (Unit 1γ).	Vertical Force (Unit 1γ).
	All Days.	Quieter Days.			
	′	′	′		
January ...	58·6	71·0	3·24	64·6	80
February ...	69·6	56·0	2·18	41·7	52
March ...	47·4	38·4	1·67	31·9	41
April	35·4	28·1	1·76	33·9	39
May	27·3	18·5	1·31	27·2	17
June	28·1	10·6	1·43	27·9	19
July	29·2	15·9	1·12	22·3	24
August ...	35·8	16·1	1·16	23·0	29
September ...	52·6	31·2	1·57	30·7	32
October ...	45·5	29·9	1·49	28·6	35
November ...	60·1	51·0	2·54	50·8	47
December ...	85·2	68·8	3·43	70·4	63

The diurnal inequalities in the Antarctic were expressed in Fourier series. Table XXXVI. gives the amplitudes of the 24-hour terms for all months of the year for *D* (all days and quieter days), *I*, *H* and *V*, and the arithmetic means of the twelve monthly values. The progres-

sion from the midwinter minimum to the midsummer maximum is remarkably smooth. Except in the case of the quieter day *D* values—where the reduction at midwinter is outstanding—the difference between midsummer and midwinter is fairly similar to that seen in Kew declination (Table XXI.).

TABLE XXXVI.—*Antarctic. Amplitude of 24-hour Fourier "Wave."*

Month.	Declination.		Inclination.	Horizontal Force. (Unit 1γ.)	Vertical Force. (Unit 1γ.)
	All Days.	Quieter Days.			
	′	′	′		
January ...	25·4	28·8	1·51	29·4	27·6
February ...	29·3	24·2	0·96	18·4	19·3
March ...	21·9	15·9	0·85	16·2	18·6
April	16·0	10·9	0·77	15·1	17·2
May	12·2	8·1	0·64	12·9	7·1
June	12·7	4·4	0·67	13·5	8·7
July	12·8	7·1	0·52	10·5	11·0
August ...	14·6	7·5	0·53	10·4	13·1
September ...	23·8	15·1	0·69	13·3	14·1
October ...	19·3	14·0	0·75	14·6	13·9
November ..	22·9	19·2	1·15	22·7	22·4
December ...	35·1	28·8	1·47	29·0	26·2
Arithmetic Means	20·5	15·3	0·88	17·2	16·6

Table XXXVII. gives the amplitudes of the 24-, 12-, 8- and 6-hour terms for the year and three seasons. Equinox contains the usual four months, but midwinter only three months (May to July) and mid-summer only three months (November to January). The closeness of approach of the amplitudes of the 24-hour terms in the mean diurnal inequality for the year to the arithmetic means given in Table XXXVI., signifies that the variability of the phase angle of the 24-hour term throughout the year is exceptionally small. Another noteworthy feature is that the mid-summer amplitudes are invariably much the largest. It will be remembered that at Kew (Tables XXI. and XXII.)

the amplitudes of the 8- and 6-hour terms were largest in Equinox.

TABLE XXXVII.—*Antarctic. Amplitudes of Diurnal Inequality Fourier "Waves."*

	Season.	Declination. All Days.	Declination. Quieter Days.	Inclination.	Horizontal Force. (Unit 1γ.)	Vertical Force. (Unit 1γ.)
		′	′	′		
c_1	Year	20·4	15·2	0·85	16·7	15·3
	Midwinter	12·5	6·5	0·61	12·3	8·8
	Equinox	20·2	14·0	0·76	14·8	15·5
	Midsummer	27·5	25·3	1·35	26·5	23·6
c_2	Year	4·4	3·5	0·16	3·1	3·5
	Midwinter	2·8	1·2	0·13	2·8	1·1
	Equinox	4·6	3·3	0·15	2·9	3·4
	Midsummer	5·7	7·6	0·23	4·5	6·9
c_3	Year	0·3	1·0	0·02	0·5	1·9
	Midwinter	0·6	0·5	0·04	0·8	0·3
	Equinox	0·2	0·4	0·03	0·7	1·6
	Midsummer	1·5	2·7	0·08	1·6	3·9
c_4	Year	0·7	0·6	0·02	0·4	1·0
	Midwinter	0·4	0·2	0·02	0·7	0·1
	Equinox	0·7	0·6	0·01	0·1	0·9
	Midsummer	1·5	1·5	0·05	0·9	2·1

Table XXXVIII. gives the ratios borne by the arithmetic means of the twelve monthly values of the amplitudes of the 12-, 8- and 6-hour waves to the corresponding mean amplitude of the 24-hour wave, for D (quieter and all days), I, H and V. The mean of the five ratios is contrasted with the corresponding ratio obtained in the case of Kew declination. As compared with the 24-hour term, the 12- and 8-hour terms possess in the Antarctic only about one-third of the

importance which they possess at Kew. The reduction in the relative importance of the Antarctic 6-hour term, though less, is also considerable. Thus the approach in the regular diurnal inequality to a single 24-hour wave is immensely closer in the Antarctic than it is at Kew or at other stations in temperate latitudes.

TABLE XXXVIII.—*Antarctic Diurnal Inequalities. Ratios of Amplitudes of Fourier "Waves."*

	Declination.		I.	H.	V.	Antarctic. All elements. Mean.	Kew D.
	Quieter days.	All days.					
c_2/c_1	0·264	0·235	0·197	0·200	0·236	0·217	0·615
c_3/c_1	0·081	0·059	0·064	0·069	0·143	0·084	0·272
c_4/c_1	0·077	0·064	0·056	0·058	0·068	0·061	0·094

Table XXXIX. gives the ratios of the amplitudes of the shorter period Fourier waves to that of the 24-hour wave in the mean diurnal inequalities from the year and the three seasons. The values are means obtained from *D*, *I*, *H* and *V*. The ratios c_2/c_1 show remarkably little seasonal variation.

TABLE XXXIX.—*Antarctic Diurnal Inequalities. Ratios of Amplitudes of Fourier "Waves."*

	Year.	Mid-Winter.	Equinox.	Mid-Summer.
c_2/c_1	0·205	0·200	0·211	0·210
c_3/c_1	0·048	0·053	0·049	0·084
c_4/c_1	0·036	0·032	0·028	0·054

Table XL. gives the phase angles of the 24- and 12-hour Fourier waves for the diurnal inequalities of the year and the seasons, and those of the 8- and 6-hour waves for the year. Local mean time is used as in the

inequality tables. The seasonal variation in the 24-hour term phase angle is remarkably small, especially in *D*. The phase angle for this element from quieter days is invariably in excess of that from all days.

TABLE XL.—*Antarctic. Phase Angles of Diurnal Inequality Fourier "Waves."*

Season.	Declination. All days.	Declination. Quieter days.	Inclination.	Horizontal force.	Vertical force.
	°	°	°	°	°
a_1 Year	338	342	50	227	87
a_1 Midwinter	336	340	57	233	111
a_1 Equinox	344	345	61	238	92
a_1 Midsummer	338	342	37	214	74
a_2 Year	133	151	200	15	241
a_2 Midwinter	91	102	188	6	234
a_2 Equinox	140	143	202	20	221
a_2 Midsummer	148	173	211	24	264
a_3 Year	66	70	292	93	45
a_4 Year	217	230	234	40	287

The annual variations in the ranges, the average departures from the mean, and the amplitudes of the 24-hour terms were analysed in Fourier Series, and the results appear in Table XLI. Only the annual and semi-annual terms were calculated. The notation is the same as in Table XXVI., Chapter VIII.

Relatively to the mean value of the element, the amplitude of the annual term is on the average somewhat smaller, and that of the semi-annual term somewhat larger than at Kew. A noteworthy feature is the similarity between the results obtained for the range, the average departure from the mean and c_1.

TABLE XLI.—*Antarctic Annual Variation. Fourier Co-efficients.*

		P_1	P_2	θ_1	θ_2	P_1/M	P_2/M	P_2/P_1
		′	′	°	°			
D (all days) ...	Range	22·3	3·8	99	49	0·46	0·08	0·17
	Average departure	5·5	1·1	96	19	0·42	0·08	0·20
	c_1	8·7	1·7	95	24	0·43	0·08	0·19
		′	′					
D (quieter days)	Range	27·2	5·9	86	70	0·75	0·16	0·22
	Average departure	6·9	1·5	89	50	0·71	0·15	0·22
	c_1	10·9	2·4	89	52	0·71	0·16	0·22
		′	′					
I	Range	0·92	0·41	88	106	0·48	0·22	0·45
	Average departure	0·25	0·10	86	109	0·44	0·18	0·40
	c_1	0·40	0·17	86	108	0·46	0·19	0·42
		γ	γ					
H	Range	18·2	9·3	88	109	0·48	0·25	0·51
	Average departure	4·9	2·2	87	112	0·44	0·20	0·46
	c_1	7·7	3·6	86	111	0·45	0·21	0·47
		γ	γ					
V	Range	19·8	7·3	87	49	0·50	0·18	0·37
	Average departure	5·4	1·4	87	48	0·50	0·13	0·26
	c_1	8·1	1·7	89	56	0·49	0·10	0·21
Means from Antarctic				90	75	0·46	0·16	0·34
,, ,, Kew				272	263	0·54	0·12	0·22

The remarkable accordance of the phase angles will be perhaps better appreciated after consulting Table XLII., which gives the date of occurrence of the maximum of the annual term, and of the summer maximum in the semi-annual term.

Large as are the amplitudes of the regular diurnal inequalities, they give a very imperfect idea of the activity of the Antarctic magnetic forces. A more adequate conception is derivable from the absolute daily ranges. Table XLIII. gives particulars of the greatest and least daily ranges for each month from March 1902 to December 1903. Only those days are included for which the record

TABLE XLII.—*Antarctic. Dates of Maxima in Annual and Semi-annual Terms.*

		Annual term.	Semi-annual term.
D (all days)	Range...	December 23	January 21
	Average departure ...	„ 26	February 5
	c_1...	„ 27	„ 3
D (quieter days) ...	Range...	January 4	January 11
	Average departure ...	„ 1	„ 21
	c_1...	„ 2	„ 20
I	Range...	January 3	December 23
	Average departure ...	„ 4	„ 22
	c_1...	„ 5	„ 22
H	Range...	January 2	December 22
	Average departure ...	„ 3	„ 20
	c_1...	„ 4	„ 21
V	Range...	January 4	January 22
	Average departure ...	„ 4	„ 22
	c_1...	„ 2	„ 18

was practically complete, except through the trace going beyond the limits of registration. Ranges less than the minima given in Table XLIII. were recorded during some months on days on which the trace was interrupted at a time when the maximum or minimum was believed to have occurred.

The extreme width of the photographic sheet represented a range of from 4°50′ to 4°56′ in D, the paper not being absolutely uniform. When the table describes the range as in excess of some value over 4°50′, the trace on at least one day of the month—sometimes on several days—had got off the sheet, first on one side, then on the other.

On some days the range was probably very considerably over 5°. During the last three months of 1903, owing to the approaching exhaustion of the photographic paper, the magnetographs were in operation for only a comparatively small number of complete days, and the

minima recorded would thus not have been fairly representative.

TABLE XLIII.—*Antarctic. Largest and Least Absolute Daily Ranges.*

Month.	Declination.		Horizontal Force. (Unit 1γ.)		Vertical Force. (Unit 1γ.)	
	Largest.	Least.	Largest.	Least.	Largest.	Least.
1902.	° ′	° ′				
March ...	>2 46·5	45·8	>196	—	162	44
April	>3 33·0	22·5	>216	36	190	50
May	3 33·0	12·8	>224	30	168	28
June	2 22·0	11·1	>160	19	166	39
July	>3 23·0	11·0	159	23	165	15
August ...	>3 30·7	20·3	>153	25	174	36
September ...	2 53·2	29·0	>112	29	92	39
October ...	>4 47·1	50·7	>111	40	155	31
November ...	>4 54·0	58·7	>160	52	303	35
December ...	>4 55·5	1 28·8	>161	93	233	60
1903.						
January ...	4 2·7	1 22·2	>161	84	415	94
February ...	>4 54·0	1 5·7	>115	58	101	92
March ...	>3 24·0	39·6	>114	32	232	25
April	>3 47·0	47·1	>144	30	142	47
May	3 43·5	24·0	>150	29	183	30
June	>4 30·4	17·1	>154	14	209	24
July	>4 0·0	23·7	>151	36	258	27
August ...	>4 51·0	39·7	>155	32	249	31
September ...	3 58·8	1 12·3	>155	51	161	33
October ...	>4 52·5	—	>157	—	245	—
November ...	>4 7·5	—	>153	—	164	—
December ...	>4 54·0	—	>160	—	318	—

For several reasons individual *H* and *V* data in Table XLIII. are less trustworthy than those for *D*. The *H* magnetograph was so sensitive that July 1902 was the only month in which the limits of registration were not exceeded on one or more days, and during midsummer the days on which the limits were exceeded were in a majority. In the case of *V*, except during October and parts of September and November 1902, the width of the sheet represented at least 1400γ. Thus information as to the maxima daily ranges was naturally far more complete for *V* than for *H*. The Antarctic *V* trace, unlike the *D* and *H* traces, seemed not infrequently to be practically undisturbed for hours at a time, and

probably the H maxima ranges were much larger than those for V.

Table XLIV. shows the relative frequency of absolute daily D ranges of different magnitudes. The first part is confined to days in which the complete range is believed to have been shown, except through the trace going beyond the limits of registration. In a few cases one limit of registration was exceeded when the range actually shown on the sheet was under 3°. The second part of the table includes days when the magnetograph was not in action at a time when the maximum or minimum was believed to have occurred. The figures in brackets give the number of days included in the total on which the trace went beyond one or both limits of registration. By "other months" are meant February 1903 and August 1902 and 1903. The three seasons have the same significance as in Tables XXXIII., XL., etc.

TABLE XLIV.—*Antarctic. Absolute Declination Ranges. Frequency of Occurrence.*

—	Total days.	0′ to 30′.	30′ to 60′.	60′ to 120′.	120′ to 180′.	Over 180′.
Complete days :—						
Midwinter	144(6)	21	53	36	22	12
Equinox	157(27)	3	29	77	30	18
Midsummer	85(23)	0	1	15	33	36
Other months	75(8)	7	18	22	19	9
Total...	461(64)	31	101	150	104	75
Incomplete days :—						
Midwinter	33(0)	14	10	7	2	0
Equinox	51(12)	6	9	19	13	4
Midsummer	26(12)	0	0	11	7	8
Other months	10(2)	2	1	2	2	3
Total...	120(26)	22	20	39	24	15

It will be seen that midsummer is as conspicuously the season when the absolute D range was largest as mid-

winter is the season when it was least. There is here a noteworthy difference from Kew and Pavlovsk, where the maxima appeared in the equinoctial months.

Even in midwinter, only 15 per cent. of the days on which registration was complete showed a range under 30′. Of the 111 midsummer days on which records were obtained, only one showed a range under 1°. Of the 581 days complete and incomplete, 70 per cent. had a range over 1°, 38 per cent. a range over 2°, fully 15 per cent. a range over 3°, and twenty-four days or fully 4 per cent. had a range over 4°. The trace exceeded both limits of registration—representing a range of at least 4°50′—on seven days. The disturbing force required to deflect the magnet 4°50′ in the Antarctic would produce a deflection of $1\frac{3}{4}°$ at Kew. There have been only two occasions during the last twenty years when the range has had as large a value.

Table XLV. shows the distribution of the absolute *V* ranges. The seasons are the same as in Table XLIV. As with *D*, midsummer is conspicuously the season when the absolute range is largest. At that season the range exceeded 100γ on seven days out of ten. Of the whole 317 days dealt with in the table only five had a range as small as 25γ, while 101, or 32 per cent., had a range exceeding 100γ.

TABLE XLV.—*Antarctic. Absolute V. Ranges. Frequency of Occurrence.*

Season.	Total Days.	0 to 50γ.	50γ to 100γ.	100γ to 200γ.	Over 200γ.
Midwinter	123	47	53	20	3
Equinox	101	20	49	29	3
Midsummer... ...	47	3	10	24	10
Other months ...	46	10	24	10	2
Total	317	80	136	83	18

Owing to the great loss of H trace, deductions as to absolute ranges in that element tend to be under-estimates. Of 569 days the trace of which was measured, whether complete or not, 60 per cent. gave a range over 75γ, and 40 per cent. a range over 100γ. This latter figure is about the same as the percentage of days which gave a D range over 2°. As it required a force of about 230γ acting perpendicular to the magnetic meridian to alter the declination by 2°, we should infer that the diurnal range of force in the Antarctic tended to be considerably larger for the component perpendicular to the magnetic meridian than for that in the meridian. This is of course obvious at once from Fig. 16 so far as the regular diurnal inequality is concerned, but what is true of the regular need not also be true of the irregular movements.

Table XLVI. shows the occurrence of the daily maxima and minima. The frequencies for successive four-hour intervals are expressed as percentages of the total.

TABLE XLVI.—*Percentage Frequency of Occurrence of Daily Maxima and Minima.*

Four hours ending—		4 a.m.	8 a.m.	Noon.	4 p.m.	8 p.m.	Midnight.
D. ...	Maxima... ...	5·9	32·6	54·5	4·7	0·4	1·8
	Minima... ...	5·3	5·7	5·5	11·7	53·5	18·5
H. ...	Maxima... ...	0·4	1·5	13·6	57·7	25·8	1·1
	Minima... ...	27·0	37·6	4·2	1·1	2·4	27·6
V. ...	Maxima... ...	39·4	8·6	5·7	2·8	13·8	29·6
	Minima... ...	2·2	10·1	43·4	31·8	5·8	6·6

In the mean D diurnal inequalities for the year and the seasons, the maximum presented itself at 9 a.m. or 10 a.m., and of the individual daily maxima 39 per cent. presented themselves between 8 and 10 a.m. Again, 6 p.m. or 7 p.m. was the hour of the minimum in the

mean D diurnal inequalities for the year and the seasons, and of the individual daily minima $53\frac{1}{2}$ per cent. occurred between 4 and 8 p.m.

There is a similar concentration of the H daily maxima round the hours 2 p.m. and 3 p.m., when the maximum appeared in the diurnal inequality. The minimum in the H diurnal inequality was rather less accentuated than the maximum, the apparent time of its occurrence fluctuating somewhat from month to month. This is reflected by the figures in Table XLVI.

In V, the annual and seasonal diurnal inequalities had the minimum at noon or 1 p.m., the maximum occurring towards midnight. Thus, in this, as in the other elements, the regular diurnal inequality exerted a dominant influence on the times of occurrence of the maximum and minimum on individual days.

The absolute range may be identical on two days, one of which was disturbed during only a few minutes, while the other was disturbed during the whole twenty-four hours, the trace showing numerous large oscillations. A perfectly fair standard of comparison would require account to be taken of all the oscillations and not merely of the largest one. Various suggestions have been made as to the basis of such a comparison, but none has met with general approval. Unless a criterion that has to be applied to all days is simple, it involves excessive demands on the time of observatory assistants, whose number is usually exiguous.

In the case of the Antarctic, however, a further comparison proved feasible. A series of "term-hours"—two a month—had been pre-arranged during which the magnetographs of the Christchurch Observatory, New Zealand (Lat. 43°32′ S., Long. 172°37′ E.), were run at a special high speed. These quick-run traces were subsequently measured at twenty-second intervals by the Christchurch staff. The Christchurch measurements were

sent to Kew and a comparison was made between the ranges of the magnetic elements there and in the Antarctic for each individual term-hour. Table XLVII. gives the means derived from these hourly ranges, and also corresponding mean daily ranges as given by hourly measurements made on the days containing the term-hours. Use was made of all the term-hours—nineteen for *D* and sixteen for *H*—during which the Christchurch and and Antarctic records were both complete. Each successive term-hour was later by one hour than the previous; thus different portions of the day were fairly represented.

TABLE XLVII.—*Antarctic and Christchurch Term Hour and Term Day Ranges.*

	Hourly Range.			Daily Range.		
	D.		*H.*	*D.*		*H.*
	Arc.	Force.		Arc.	Force.	
	′	γ	γ	′	γ	γ
Antarctic	28·2	54	20·5	84	161	62
Christchurch...	1·04	6·9	3·1	6·8	45	25·8
Ratio	27·2	7·9	6·7	12·4	3·6	2·4

The table shows that on the average term-hour the extreme positions of the Antarctic *D* magnet differed by 28′·2, or no less than 27·2 times the corresponding hourly range at Christchurch. When expressed in terms of force, the hourly *D* range at Winter Quarters becomes 7·9 times that at Christchurch.

The hourly ranges represent the activity of magnetic forces in the Antarctic as much greater relatively than do the daily ranges. The changes in the magnetic elements at Christchurch were mainly dependent on the regular diurnal inequality, whereas at Winter Quarters the ranges were very largely determined by irregular disturbances.

CHAPTER XI

MAGNETIC STORMS

By "magnetic storm" is meant a disturbed condition of the magnetic elements. The term is, however, usually restricted to the larger disturbances. The term "disturbance" itself has been employed in a variety of senses. General Sabine regarded a reading as disturbed when it differed by more than a specified amount from the mean reading at that hour for the month. We have seen, however, that the regular diurnal inequality characteristic of a particular month depends on the species of day from which it is derived, and the inequality from any given species of day for any month of the twelve varies with sunspot frequency. Thus Sabine's definition is more arbitrary than might appear at first sight.

When large oscillatory magnetic changes are in progress, the trace of a particular element may cross and recross the curve representing the regular diurnal inequality for any particular type of day. At the instant when such a crossing took place the *reading* according to Sabine's definition would not be disturbed, but if the oscillations were large and frequent few people would hesitate to describe the *element* as disturbed. In practice, one usually regards a portion of curve as quiet or disturbed according as its course is or is not free from sinuosities of short period. This, however, does not cover all cases, for the curve may be of an obviously abnormal character, though not oscillatory.

Fig. 17 gives examples of three types of disturbance copied from actual Kew curves. The time scale is shown at the foot. The movements to which the letter

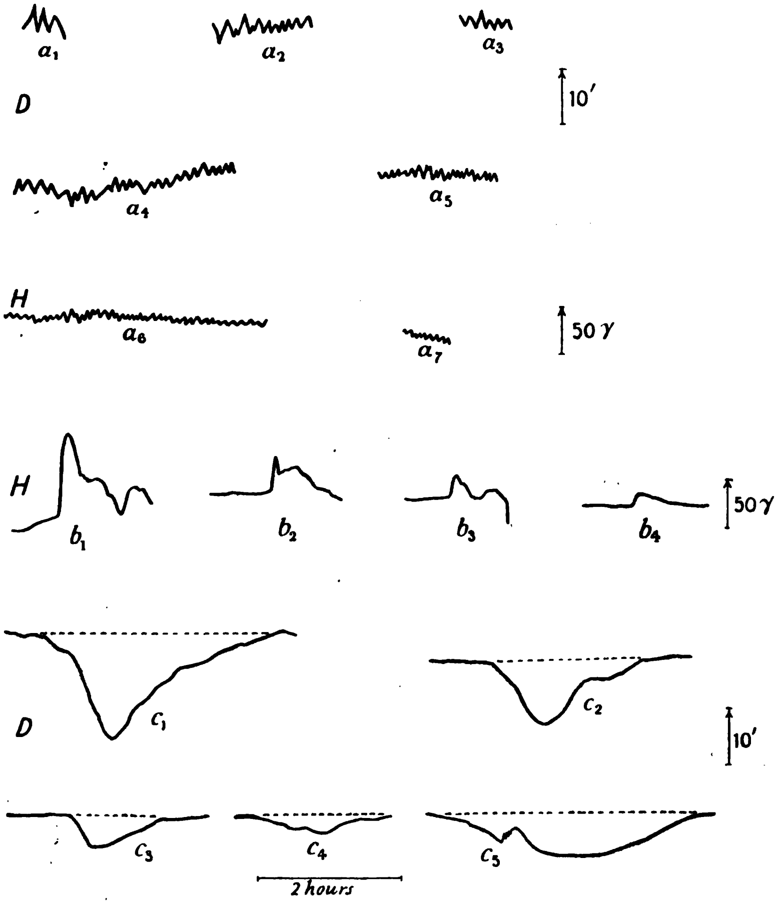


FIG. 17.—TYPES OF DISTURBANCE AT KEW.

"*a*" is attached are conspicuously oscillatory. They are of a type not uncommon in *D* and *H* traces, but seldom seen in Kew *V* traces. Larger movements of the kind are sufficiently illustrated in some

of the magnetic storms reproduced presently. These markedly oscillatory movements are numerous in some, but by no means in all magnetic storms. Also, when of small amplitude, as in a_5, a_6, and a_7, they occur not infrequently on days that are otherwise very quiet. The small movements seen on quiet days have been termed "pulsations" by Dr. van Bemmelen. The term is especially appropriate in such a case as a_7, where the successive movements closely resemble one another. In other instances, for example, in a_2 and a_4, the appearance of the curve suggests the superposition of two or more sets of elementary pulsations of different periods. In the cases illustrated in Fig. 17, the interval from crest to crest represents from two to ten minutes and has nothing to do with the natural oscillation period of the magnet, which is of the order of ten seconds. When Kew pattern magnetograph magnets are set swinging, what the usual slow-run trace shows is an indistinct burr. At some stations quick-run traces have shown pulsations of only a few seconds' period.

The disturbances in Fig. 17 distinguished by the letter "*b*" are especially characteristic of the *H* trace. They form the first or introductory movement in a number of magnetic storms, being then usually known as "sudden commencements." The term, however, is only relative, as the movement in one direction usually lasts for several minutes. The examples shown are all from *H* curves, and the commencing movement in all is up the sheet, representing a rise in *H*. This is what usually happens, but it is not uncommon for the movement up the sheet to be preceded by a much smaller movement down the sheet, occupying only a minute or less. The downward movement is usually small and short-lived, and it is by no means unlikely that it occurs occasionally without leaving any recognisable mark on the sheet. The association of movements of type *b* with magnetic storms

has a dramatic feature about it which appeals to the imagination. It is thus desirable to mention that the association is by no means invariable. For instance, b_4 was not followed by any disturbance worth mentioning.

The "*c*" movements in Fig. 17 represent a phenomenon not uncommon in the Kew *D* trace. The dotted line is intended to show what the trace would naturally have been in the absence of disturbance. The disturbed curve lies entirely on one side of the normal position. Sometimes, as in c_3, the trace is conspicuously regular both before and after the "bay," the term usually applied to this type of disturbance.

The "*c*" record is such as we should get if we sent an electric current along a straight wire in the magnetic meridian in the neighbourhood of the declination magnet, and either moved the wire slowly towards the magnet and withdrew it, or else gradually increased and then diminished the current. The record of a "bay" is often free or nearly so from any sensible short period oscillations. The rapid oscillations seen in c_5 arise most probably from an independent source of disturbance, happening to synchronise with that to which "the bay" is due.

An apparent tendency in "bays" to happen about the same hour on successive days was observed long ago by Senhor Capello of Lisbon, and is discussed by Dr. Balfour Stewart in the ninth edition of the *Encyclopædia Britannica.*[1] Without expressing a decided opinion as to whether the apparent "repetition" was real or accidental, he suggested that if the former alternative should prove to be true, the phenomenon might arise through some particular portion of the earth's atmosphere assuming and retaining for over twenty-four hours a sensitive state—or, as we should now say, an ionised condition—such that when

[1] Terrestrial Magnetism (under Meteorology), § 87.

the diurnal rotation brought it opposite the sun electrical currents passed.

Fig. 18 shows examples of apparent repetitions of "bays" in Kew *D* curves, all occurring between the 7th and 18th of February, 1911. On the 7th, 8th, and 9th, there are "bays" all showing the maximum departure from the normal about 6 p.m., and the displacements at this hour

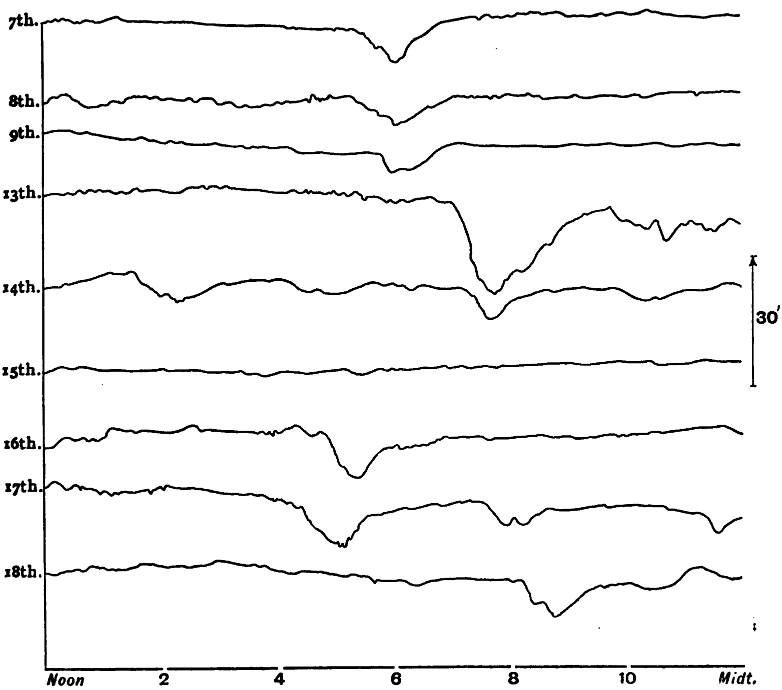


FIG. 18.—"BAYS" IN KEW DECLINATION CURVES.

are much the most conspicuous on the respective afternoons. A very deep "bay," centring about 8 p.m. on the 13th is followed on the 14th by a much shallower "bay" centring at the same hour. The next afternoon was exceptionally quiet. On the 17th there are two "bays," one centring about 5 p.m., and closely resembling a "bay" centring a very little later on the 16th, and a second centring about 8 p.m. which resembles a "bay"

centring a little later on the 18th. The sequence on the 13th and 14th is unquestionably much in harmony with Balfour Stewart's suggestion. In many cases, however, as in the 16th, 17th, and 18th, the "repetition" occurs at a sensibly different hour, which would entail a considerable shift of the ionised portion of atmosphere in the course of twenty-four hours.

Fresh light was thrown on the phenomena of "bays" by the Norwegian Arctic observations and the British Antarctic observations of 1902–3. Prof. Kr. Birkeland, dealing with the magnetograph records in the Arctic, found a good many instances in which disturbances of the *c* type in Fig. 17 occurred simultaneously with what he called "elementary polar" storms in the Arctic, and the present writer dealing with Antarctic records noticed the frequent occurrence of a "special type of disturbance" which seems the counterpart of those observed in the Arctic. Disturbances of a "bay" type synchronous with the Antarctic storms were traced through Christchurch, N.Z., Mauritius, and Colaba (Bombay), as far as Kew; while Birkeland traced disturbances synchronous with his "elementary polar" storms as far as Christchurch. The essential feature of the "elementary polar" storm, or the Antarctic "special type of disturbance," is a single oscillation, the force returning approximately to its original value. Fig. 19 shows side by side three of these Antarctic disturbances, all recorded in June, 1903, and two on successive days, the 28th and 29th. Movement up the sheet in the Antarctic curves represented increase of V, but diminution of D and H. Thus in all three cases the first movement or "phase" represents a fall in all three elements, while the second phase represents a rise. Superposed on the main oscillation are minor oscillations, from which the Antarctic curves were practically never free.

Before discussing in detail the Antarctic "special type

of disturbance" and its relationship to disturbances elsewhere, it is convenient to describe other forms of disturbance in the Antarctic curves. In *a* and *b* of Fig. 20 we have examples of disturbances resembling a succession of waves. In *a* four successive oscillations can be traced, the two central being the largest. The individual oscillations bear a resemblance to disturbances of the "special

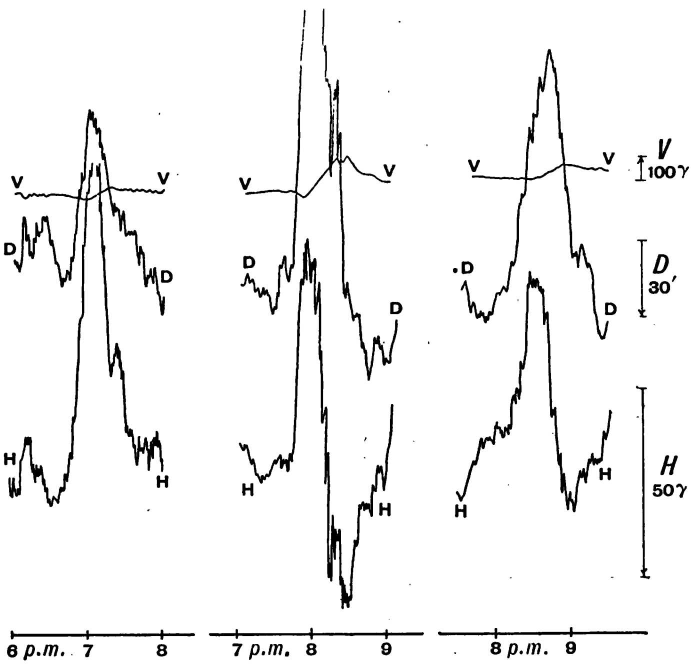


FIG. 19.—ANTARCTIC "SPECIAL TYPE OF DISTURBANCE."

type." The oscillations, however, in the *D* and *H* traces do not seem exactly in phase towards the end. There is no *D* trace in *b*, which shows a succession of oscillations having a considerably shorter period than in *a*.

In *a*, *b*, *c*, Fig. 21, we have examples of still more rapid Antarctic oscillations. The scale values in Figs. 20 and 21 can be inferred from the values given for the ranges during the respective intervals. Taking in order Figs. 19

to 21, we see a gradual transition from the single oscillation of the "special type of disturbance" to the frequently repeated short period oscillations. It is difficult to say whether there is a fundamental difference in type or merely a difference in period between the several cases. Of the apparent differences, the one that seems most outstanding is that the oscillation seems to be almost

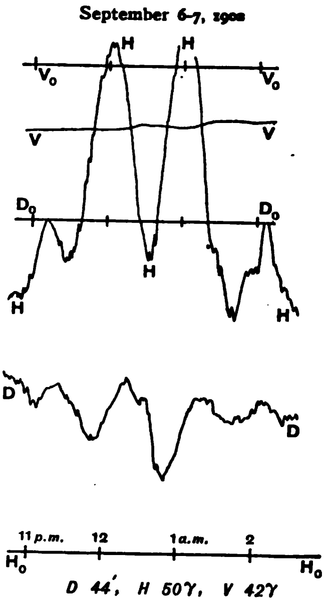


FIG. 20*a*.

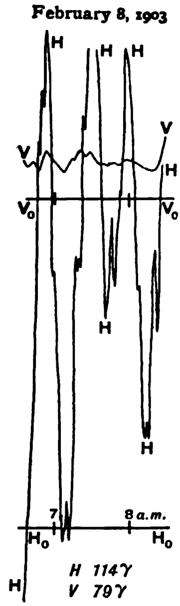


FIG. 20*b*.

ANTARCTIC TYPES OF DISTURBANCE.

entirely on one side of the normal in the "special type of disturbance," whereas in the shorter period disturbances this does not appear to be the case.

Examination of the Antarctic curves for 1902 and 1903 disclosed eighty-two clear occurrences of the "special type of disturbance." Table XLVIII. shows their incidence throughout the year, and the average duration in minutes of the two phases described above.

TABLE XLVIII.—*Occurrences of the "Special Type of Disturbance."*

—	April and May.	June.	July.	August.	September.	Other months.
Number	11	16	18	22	4	11
Length, 1st phase	15·2	17·1	15·4	18·3	21·7	16·9
,, 2nd ,, ...	19·5	19·9	19·6	20·1	21·5	24·3

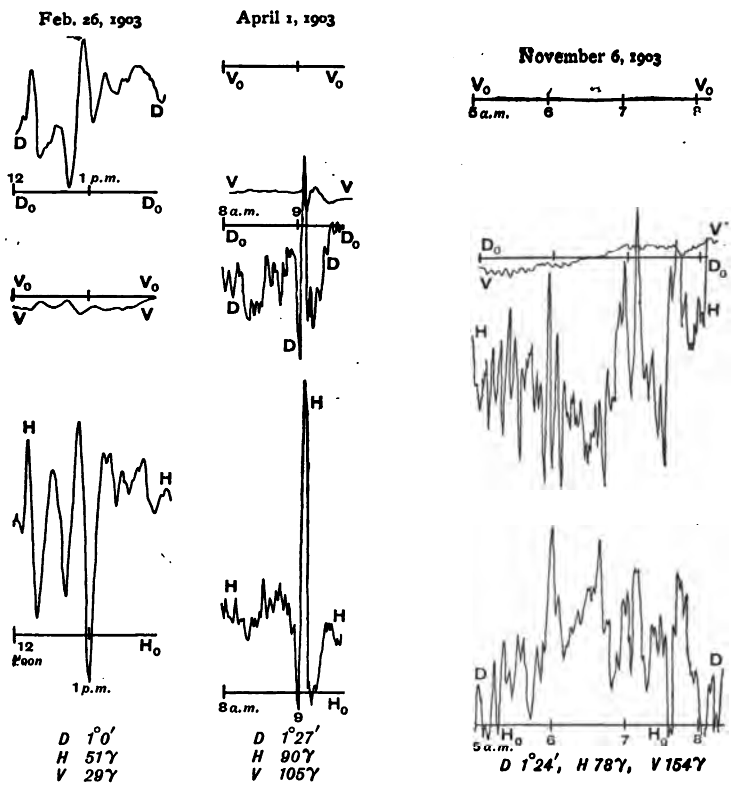


FIG. 21*a*. FIG. 21*b*. FIG. 21*c*.

ANTARCTIC TYPES OF DISTURBANCE.

There were many cases not included in Table XLVIII. which resembled the "special type of disturbance." On highly disturbed days the movements were so large and rapid that it was difficult to disentangle the general features of the curve. The "special type of disturbance"

showed a marked preference not merely for one season of the year, midwinter, but also for one part of the day. Of the eighty-two cases included in Table XLVIII. seventy-eight culminated between 3 p.m. and midnight, and forty-two of these between 7 and 9 p.m. L.M.T. Considering the marked preference for midwinter and for the hours 7 to 9 p.m., we see that the argument for a direct connection between such occurrences as those of June 28 and 29, 1903, is much weakened.

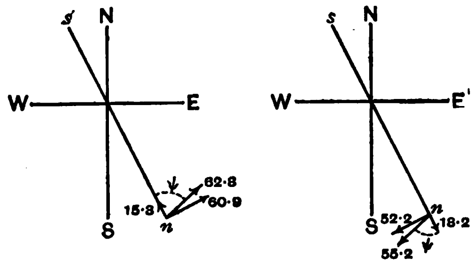
Table XLIX. gives particulars as to the amplitude and direction of the forces to which might be ascribed the changes in the magnetic elements during the two phases of the special type of disturbance. The means given for the different months show the persistence in type of the phenomenon.

TABLE XLIX.—"*Special Type of Disturbance.*"

—		First phase.			Second phase.		
Months.	Number.	ΔT.	ψ.	χ.	ΔT.	ψ.	χ.
			°	°		°	°
April and May.	6	63·7	71·4	−7·2	59·0	57·4	+21·7
June	11	61·3	81·4	−6·5	47·9	63·7	+26·1
July...	13	63·5	77·4	−5·0	61·5	73·4	+19·8
August	17	50·9	82·5	−5·1	54·0	78·7	+18·4
September ...	4	112·0	73·5	−5·0	109·8	68·3	+19·6
All	51	63·1	75·9	−5·6	59·1	70·8	+20·8

Use is made only of the cases in which the record was quite complete. ΔT denotes the intensity (in γ) of the resultant force, ψ is its inclination in the horizontal plane to the local magnetic meridian, and χ the inclination to the horizontal plane, the positive or negative sign being attached according as the vector is directed upwards or downwards. Fig. 22 shows for the two phases how ψ is measured; it also gives for the average disturbance of Table XLIX. the horizontal components of ΔT in and

perpendicular to the local magnetic meridian *sn* and their resultant. NS and EW represent geographical north-south and east-west.



First Phase. Second Phase.

FIG. 22.—ANTARCTIC "SPECIAL TYPE OF DISTURBANCE."

So far as the horizontal components of force are concerned, the second phase may be regarded as in the main a relaxation of the forces to which the first phase is due.

The relaxation in the average disturbance is not quite complete, this deficiency being represented by the difference between the 62·8γ of the first phase and the 55·2γ of the second. There is also a small rotation of the vector as indicated by the difference (5°·1 on the average) between the values of ψ in the two phases. In the case, however, of V the fall in the first phase averaged only 6·1γ, while the rise in the second phase averaged 21·0γ. Thus the passage of a disturbance of the "special type" produces ordinarily a rise in the vertical force, which only gradually disappears.

Of the disturbances of the "special type" those of June 19, 28, 29, and July 26, 1903, were amongst the principal. The Antarctic records for these dates were compared with the corresponding records from the nearest magnetic observatory, that of Christchurch, New Zealand, and with the Kew records. Curves from Colaba (Bombay) were also available for July 26. The disturbance was in all cases of a "bay" type, and so divisible into two principal phases, the departure from the normal increasing up to

the end of the first phase, or culmination, and then diminishing—so far as the horizontal component was concerned—during the second phase.

Table L. gives the amplitude and direction of forces which would have produced at the several stations the changes shown by the traces during the times assigned to the first and second phases respectively. The Antarctic traces in several of the four cases were not quite complete near the culmination, and the values assigned in these cases to the disturbing forces are to some extent underestimates.

ΔX, ΔY, ΔZ represent the components of the forces referred to three rectangular axes, that of z coincident with the earth's axis, those of y and x being perpendiculars on the axis of z answering respectively to longitudes of 0° (Greenwich) and 90° East. The positive directions are for z to the north, for y and x outwards.

ΔR, θ, ϕ represent the same force system in polar co-ordinates such that

$$\theta = \cos^{-1}(\Delta Z/\Delta R),\ \phi = \tan^{-1}(\Delta X/\Delta Y).$$

The unit of force employed in Table L. is 1γ.

Table L.—more especially the values of θ and ϕ—shows the resemblance existing between the individual Antarctic disturbances. The first phases in all may be regarded as of one type called *B*, and the second phases as of a different type called *A*. For purposes of comparison Table L. gives for the Antarctic station results for a mean disturbance representing those of June 19, 28, 29, and July 26, 1903, and also for a mean disturbance representing the fifty-one disturbances included in Table XLIX. The corresponding values of ϕ in the two cases come very close.

The Kew disturbances in Table L. may also be regarded as roughly of two types, *B* and *A*, though the second phase on June 19—which was too small to give very

TABLE L.—*Analysis of Disturbances of the "Special Type."*

		ΔX.	ΔY.	ΔZ.	ΔR.	θ.	φ.	Type.
Winter Quarters.						°	°	
June 19	1st phase ...	− 48	− 151	+ 49	166	73	198	*B*
	2nd ,, ...	+ 30	+ 86	− 71	116	128	19	*A*
June 28	1st ,, ...	− 131	− 186	+ 62	236	75	215	*B*
	2nd ,, ...	+ 56	+ 132	− 174	225	140	23	*A*
June 29	1st ,, ...	− 104	− 137	+ 26	174	81	217	*B*
	2nd ,, ...	+ 83	+ 135	− 78	177	116	32	*A*
July 26	1st ,, ...	− 234	− 112	− 12	260	93	244	*B*
	2nd ,, ...	+ 198	+ 137	− 96	259	112	55	*A*
Mean 4 cases	1st ,, ...	− 129	− 146	+ 31	198	81	221	*B*
	2nd ,, ...	+ 92	+ 122	− 105	186	124	37	*A*
Mean all complete cases	1st ,, ...	−37·1	−48·8	+14·7	63·0	77	217	*B*
	2nd ,, ...	+29·3	+42·4	−29·0	59·1	93	35	*A*
Christchurch.								
June 19	1st phase ...	+41·2	+ 7·8	+ 6·5	42·4	81	79	*C*
	2nd ,, ...	−34·8	−24·0	+11·9	43·9	74	235	*A*
June 28	1st ,, ...	+35·8	+10·1	+ 0·7	37·2	89	74	*C*
	2nd ,, ...	−22·1	−17·5	+ 8·8	29·5	73	232	*A*
June 29	1st ,, ...	+ 3·9	− 0·3	+ 0·8	4·0	78	94	*C*
	2nd ,, ...	+15·1	+13·5	−12·2	23·6	121	48	*B*
July 26	1st ,, ...	+28·4	+24·1	−16·9	40·9	114	50	*B*
	2nd ,, ...	−31·8	−11·5	− 4·2	34·1	97	250	*A*
Colaba.								
July 26	1st phase ...	+ 8·6	+ 0·3	−24·2	25·7	160	88	*B*
	2nd ,, ...	− 0·3	− 5·8	+ 5·8	8·2	45	183	*A*
Kew.								
June 19	1st phase ...	+ 2·1	+ 9·7	− 7·8	12·6	128	12	*B*
	2nd ,, ...	+ 4·6	− 1·1	+ 0·9	4·8	79	103	*A* ?
June 28	1st ,, ...	−11·8	+ 6·0	− 4·8	14·1	110	297	*B*
	2nd ,, ...	− 4·9	− 6·6	+ 5·3	9·8	57	217	*A*
June 29	1st ,, ...	− 5·1	+ 7·3	− 5·8	10·6	123	325	*B*
	2nd ,, ...	−14·7	− 0·2	+ 0·2	14·7	89	269	*A*
July 26	1st ,, ...	−11·1	+31·8	−24·1	41·4	126	341	*B*
	2nd ,, ...	−16·4	−20·3	+11·0	28·3	67	219	*A*
Mean 4 cases	1st ,, ...	− 6·5	+13·7	−10·6	18·5	125	335	*B*
	2nd ,, ...	− 7·8	− 7·0	+ 4·4	11·4	68	228	*A*

satisfactory results—shows an abnormal value for ϕ. The amplitude of the Kew disturbance was on the average only about 1/15 of that in the Antarctic.

The average Christchurch disturbance was about thrice as large as that at Kew, but for some reason there appeared more diversity of type. Provisionally three types, *A*, *B*, and *C*, have been assigned in Table L.

CHAPTER XII

"SUDDEN COMMENCEMENTS"

It was noticed long ago that a good many magnetic storms began with the "sudden commencement" illustrated in Fig. 17. Whether the "sudden commencements" at different stations are simultaneous is a question on which there is still a difference of opinion. It is difficult at the best of stations, with paper travelling at the ordinary rate—15 to 20 mm. per hour—to measure times correctly to nearer than one minute. "Sudden commencements" are far from instantaneous, lasting usually several minutes, and frequently they are not very large. Thus a finite time must elapse, depending on the sensitiveness of the magnetograph and the goodness of the photography, before the movement is large enough to be recognised. Perhaps all we are entitled to say at present is that the differences between the times assigned by different observatories to "sudden commencements" are, from the point of view of their magnitude, exactly such as might be expected *a priori* on the hypothesis that the disturbances are truly synchronous. From a theoretical standpoint we should not expect markedly larger differences of time than those necessary for the transmission of electromagnetic waves round the earth.

Fig. 23 shows a "sudden commencement" between 23 h. (11 p.m.) and mid-night (G.M.T.) on April 5, 1903. This is unusually clear owing to its large size, and to the

fact that the traces were very quiet when it began. The subsequent disturbance was only a moderate one. The uppermost and the lowest traces are for declination, at

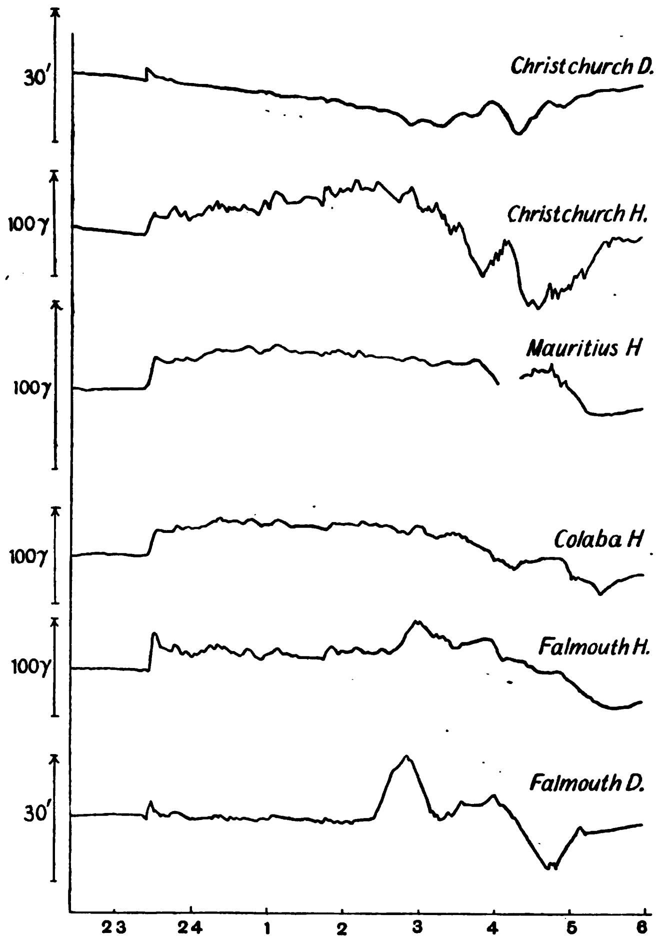


FIG. 23.—"SUDDEN COMMENCEMENT." April 5-6, 1903.

Christchurch, New Zealand, and at Falmouth respectively. Movement up the sheet represents at both places movement of the north end of the needle to the west. The four

intermediate traces are for horizontal force at Christchurch, Mauritius, Colaba and Falmouth. Movement up the sheet represents increasing force in all. The scale values are shown at the side.

Remote as the stations are from one another, there is a considerable family resemblance between the four H traces. The Falmouth curve gives at least a suggestion of the small rapid movement down the sheet which, as stated on p. 115, is occasionally seen in "sudden commencements." Omitting this, we have a rise from the commencement 11.25 p.m. (G.M.T.), which attained its maximum at all the stations at about 11.29. The excess in the value of H at 11.29 over that at 11.25 was 41γ at Falmouth or Kew, 25γ at Colaba, 18γ at Mauritius and 19γ at Christchurch. Thus the changes were not merely simultaneous, or practically so, but also of the same order of magnitude, though the extreme stations differ by over 90° of latitude, and over 175° of longitude. After 11.29 there was at all the stations a temporary fall in H, largest at Falmouth, but the element remained above its undisturbed value for several hours. In this instance the commencing D and V movements were small compared with the H. The commencing D movement, however, at Kew and Falmouth was unmistakably oscillatory.

Fig. 24 shows the phenomena in the Antarctic at the *Discovery's* Winter Quarters on April 5 to 6, 1903. The V curve is fairly quiet until the sharp oscillation which introduces markedly disturbed conditions. So far as could be judged, this and the corresponding oscillations in D and H began at the same time as the sudden commencement at the temperate stations in Fig. 23. The D and H curves before these oscillations show the minor disturbances from which the elements were never quite free in the Antarctic, but the oscillations are so outstanding relatively that they at once arrest the eye.

The first swing (down the sheet in V, up in H and D)

represents a decrease in all the elements, and though markedly less than the return swing is of a different order of magnitude from the small preliminary movement at Falmouth.

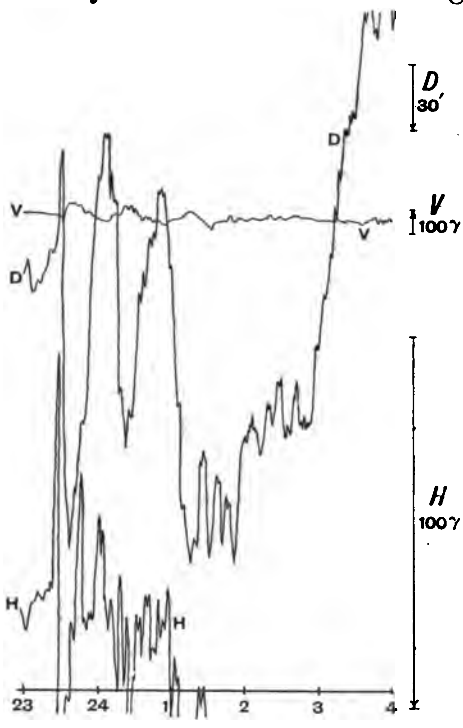


FIG. 24.—ANTARCTIC "SUDDEN COMMENCEMENT."

Table LI. contains an analysis of the forces to which might be ascribed "sudden commencements" on four occasions—May 8 and August 20, 1902, and April 5 and August 25, 1903—for which data existed from the *Discovery's* Winter Quarters in the Antarctic and the observatories of Christchurch, Colaba and Kew. The notation is the same as in Table L., and as there the unit of force is 1γ.

On August 25, 1903, an oscillation was visible at all the stations. In the table the earlier and smaller movement, which lasted about three minutes, is described as the first phase, while the principal movement, which also lasted about three minutes, is called the second phase. On the other three occasions the Antarctic curves alone showed a clear oscillation in all the elements. The force systems answering to the two movements are given separately. The force systems given for Christchurch, Colaba and Kew on the three occasions

in question represent the excess of force at the instant when the upward movement in the H curve ceased above that existing at the instant when the sudden commencement began. The letters A and B, or A, B and C, are

TABLE LI.—*Analysis of "Sudden Commencements."*

	ΔX.	ΔY.	ΔZ.	ΔR.	θ.	ϕ.	Type.
WINTER QUARTERS.					°	°	
May 8, 1902 1st phase	+ 21	+ 19	− 3·0	28	96	48	*A*
May 8, 1902 2nd „	− 38	− 36	− 0·5	52	91	227	*B*
Aug. 20, „ 1st „	− 28	− 26	+ 2·8	38	86	228	*B*
Aug. 20, „ 2nd „	+ 42	+ 43	− 0·5	60	90	45	*A*
April 5, 1903 1st „	− 14	− 88	+ 49	102	61	189	*B*
April 5, 1903 2nd „	+144	+229	−130	300	116	32	*A*
Aug. 25, „ 1st „	+ 12	− 43	+ 39	59	49	164	*B*
Aug. 25, „ 2nd „	+ 15	+115	− 77	139	123	7	*A*
CHRISTCHURCH.							
May 8, 1902	− 3·1	− 5·8	+ 6·3	9·1	46	208	*A*
Aug. 20, „	+ 3·1	− 3·1	+ 3·7	5·7	49	135	*A*
April 5, 1903	+ 7·7	−12·4	+17·2	22·6	40	148	*A*
Aug. 25, „ 1st phase	− 1·6	− 0·9	+ 0·7	2·0	69	241	*A*
Aug. 25, „ 2nd „	+ 7·2	+ 1·8	+ 1·8	7·6	76	76	*C*
COLABA.							
May 8, 1902	+ 2·7	− 7·2	+20·2	21·6	21	159	*A*
Aug. 20, „	− 1·1	− 2·6	+10·2	10·6	16	203	*A*
April 5, 1903	+ 1·0	− 4·3	+26·3	26·8	11	167	*A*
Aug. 25, „ 1st phase	+ 1·1	− 1·9	− 1·4	2·6	123	150	*B*(?)
Aug. 25, „ 2nd „	− 3·5	+ 0·1	+17·3	17·7	11	272	*A*
KEW.							
May 8, 1902	−11·9	−11·8	+ 9·4	19·2	61	225	*A*
Aug. 20, „	− 7·1	−10·4	+ 7·0	14·4	61	214	*A*
April 5, 1903	−28·8	−30·0	+17·2	45·0	68	224	*A*
Aug. 25, „ 1st phase	+ 5·3	+ 3·6	− 2·9	7·0	114	56	*B*
Aug. 25, „ 2nd „	−16·0	−24·0	+19·1	34·6	56	214	*A*

employed for the classification of the force systems under different types, and comparing the results with the corresponding results in Table L. it will be recognised that the same letters have a like significance in the two tables. The attachment of a common letter does not imply

identity but only a family resemblance. Uncertainties attached to individual values of θ and ϕ, especially in cases where the resultant force was small, and the number of instances is insufficient to warrant any very definite conclusion.

There were two other occasions of "sudden commencements" for which corresponding Kew and Antarctic records existed, viz: November 6, 1902, and December 13, 1903, making six cases in all. On each occasion the Antarctic trace showed an oscillation, and the resultant force for the first phase, though less than that for the second, was very considerable. At Kew, as we have seen, a double movement is sometimes visible; but invariably or almost invariably the dominant movement—the second when two exist—consists mainly of an increase in H and is of the type called A. Whereas of the six cases specified above in the Antarctic, the second and principal phase was thrice of type A and thrice of type B.

Taking the ratios of the amplitudes of the forces causing "sudden commencements" at the different stations to the corresponding amplitudes at Kew, the mean values obtained were for the *Discovery's* Winter Quarters 4·5, for Christchurch 0·38, for Mauritius 0·50, and for Colaba 0·67. We thus apparently have to do with disturbances which, while unmistakably greater in the Antarctic than in temperate latitudes, increase decidedly as we travel northwards from Christchurch and Mauritius to Kew. We should thus infer two maxima of disturbance, one in high southern the other in high northern latitudes, with an intervening minimum in southern latitudes.

A number of short period oscillations recognisable on the traces from Kew, Colaba, Mauritius, Christchurch, and the Antarctic for July 24th, 1902, gave relationships between the amplitudes closely similar to those observed in the case of "sudden commencements."

In the case of the "special type of disturbance" the ratios borne by the amplitudes of the disturbances at Winter Quarters and Christchurch to those at Kew were respectively 15 and 3. In the one instance, July 26th, for which data were available, the amplitude at Colaba was, however, only 0·46 that at Kew. Thus in this instance too there were presumably maxima of disturbance in high latitudes, northern and southern, with an intervening minimum.

Prof. Birkeland, on his side, identified a good many cases of apparently corresponding minor movements, not associated with his "polar elementary" storms, which were recognisable and not conspicuously different in magnitude at all his co-operating stations from Pavlovsk to Christchurch. These disturbances he described—though the numerical details seem hardly to warrant the conclusion—as largest in equatorial regions, and he ascribed them to an overhead electrical current in the magnetic equator, at a height apparently of some thousands of miles. If a current of this character existed, the intensity of which suddenly increased from zero, we should expect a sudden movement in the magnetograph magnets, the direction depending on that of the current. Near the magnetic equator, which does not depart very widely from the geographical equator, the disturbing force would be nearly in the local magnetic meridian, and not far from horizontal. Thus the movement would be chiefly exhibited by the horizontal force trace, as is indeed usually true of "sudden commencements."

As one receded from the magnetic equator, the resultant disturbing force would naturally diminish, and the vertical component increase relatively to the horizontal. In high latitudes the vertical component would naturally be the dominant one.

In the case of the "polar elementary" disturbances Prof. Birkeland supposes the cause to be a flight of

ions, the equivalent of an electrical current, overhead in Arctic regions, and at a much lower altitude than the hypothetical current causing "equatorial" disturbances. If this view is correct, then the magnitude of the disturbance should diminish rapidly as one recedes from the Arctic region where the current is overhead, and its character at any given station should vary markedly with the azimuth of the station relative to the area of maximum disturbance.

CHAPTER XIII

COMPARISON OF ARCTIC AND ANTARCTIC DISTURBANCES

Prof. Birkeland's book[1] contains twenty-one plates showing simultaneous records of disturbances from a number of co-operating stations and from his four Arctic stations, which had the following positions :—

Station.	Latitude N.	Longitude.
	° ′	° ′
Axelöen (Spitzbergen)	77 41	14 50 E.
Matotchkin Schar (Nova Zembla)	73 17	53 57 E.
Kaafjord (Finmark)...	69 56	22 58 E.
Dyrafjord (Iceland)	66 15	22 30 W.

Just before the end of the Norwegian expedition Kaafjord was replaced by Bossekop, a station only a few miles distant.

On the large majority of the occasions to which Prof. Birkeland's plates refer, corresponding Antarctic records existed from the *Discovery's* Winter Quarters. Figs. 25 to 42 each contain records copied from Prof. Birkeland's plates for one or more of his Arctic stations, corresponding H and D records taken directly from the Kew curves, and corresponding Antarctic records. The traces have been enlarged or reduced, so as to secure a common time scale. The times shown are all G.M.T., hours being counted from 0 (midnight) to 24. The ordinate scales differ widely, but at the side of each curve is shown the length of ordinate which represents a change of 50γ in force. Declination ordinate scales are expressed in terms of force. At Kew, for instance, where $H = 0{\cdot}185$, in the original curves 10 mm. of ordinate represents a change of $8'{\cdot}7$ in D,

[1] The Norwegian Aurora Polaris Expedition, 1902–1903. Vol. I.

which requires the application perpendicular to the magnetic meridian of a force $= 0{\cdot}185 \times 8{\cdot}7 \times 0{\cdot}000291 = 46{\cdot}7\gamma$.

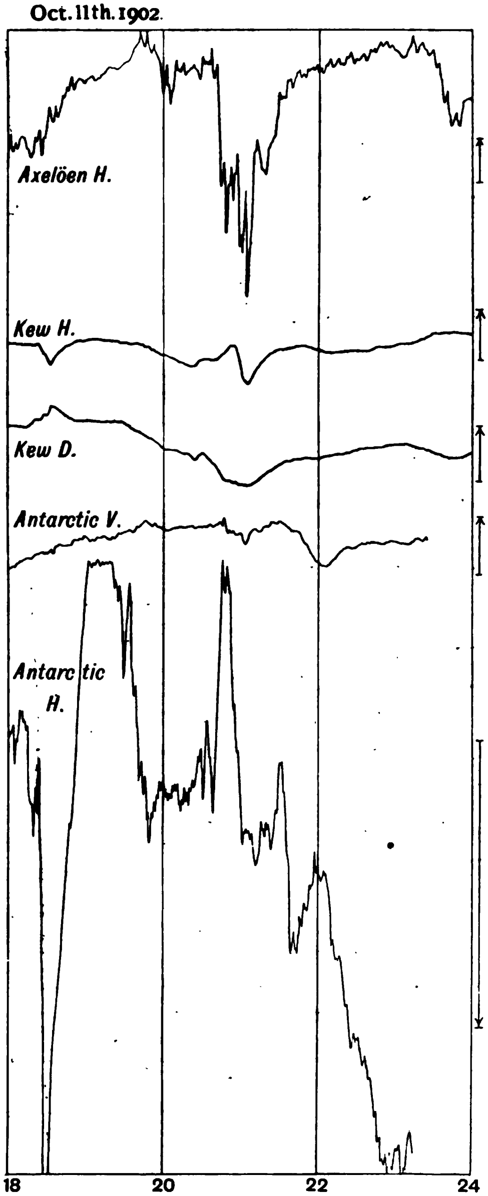


FIG. 25.—ARCTIC-KEW-ANTARCTIC CURVES.

Thus 50γ answers to 10·6 mm. of ordinate.

The arrow head on the line showing the scale value gives the direction of increasing force. At Kew H and D both increase up the sheet. In the Antarctic V increased up the sheet, but H and D down.

Fig. 25 for October 11th, 1902, answers to part of Birkeland's Plate II. The most outstanding features in the Kew curves are the peaks about 6.30 p.m., the "bay" on the D curve between 8 and 10 p.m. and the corresponding H oscillation. The movements about 6.30 p.m. are not unrepresented at Axelöen (and were better represented at Matotchkin Schar), but they

are specially manifested by the Antarctic *H* curve. Between 8 and 10 p.m. the Axelöen curve shows one of Birkeland's "polar elementary" storms, which culminated about the same time as the "bay" in the Kew *D* curve. The oscillation occurring about this time in the Kew *H* curve has a counterpart in a prominent oscillation in the Antarctic curves.

Fig. 26 for October 23, 1902, answers to part of Birkeland's Plate III. Shortly after 7 p.m. there is a rapid movement, regarded by Birkeland as the commencement of an "equatorial" perturbation. At Kew the *H* curve shows the sudden rise characteristic of "sudden commencements"—though the subsequent movements were far too small to be dignified with the title "magnetic storm." The Kew *D* curve shows a small oscillation, the Axelöen *D* curve a distinctly larger oscillation, and the Antarctic curves the largest oscillation of all.

The Axelöen curve shows a "bay" near 9 p.m., regarded by Birkeland as an "elementary polar" storm. This is represented only very slightly, if at all, at Kew. The sharp peak on the Axelöen *D* curve,

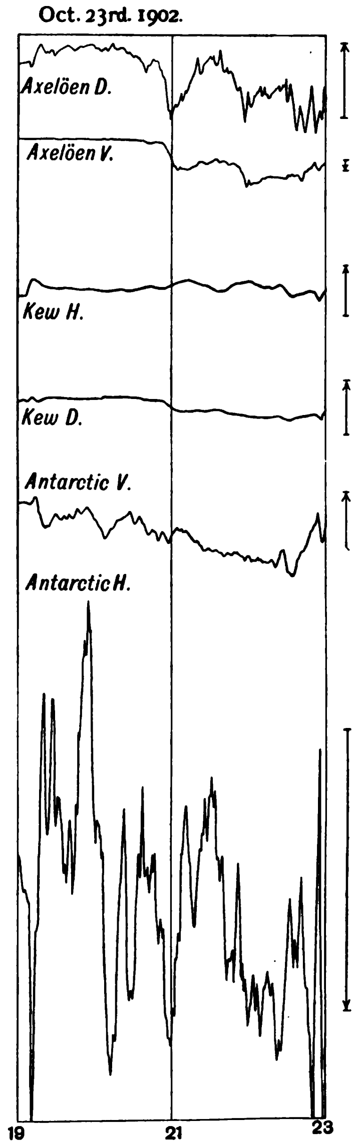


Fig. 26.
Arctic-Kew-Antarctic Curves.

representing the culmination of the "polar" storm, seems synchronous with a sharp peak on the Antarctic *H* curve. The Antarctic *V* magnetograph was exceptionally sensitive in October 1902, and the movements in this element in Fig. 26 are not really exceptionally large. Their greatest development was between 10 and 11 p.m.

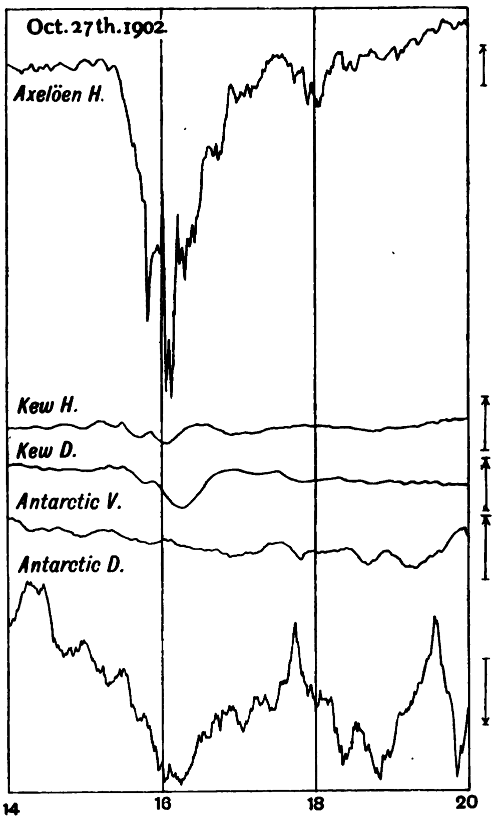


FIG. 27.—ARCTIC-KEW-ANTARCTIC CURVES.

Fig. 27 for October 27, 1902, corresponds to part of Birkeland's Plate IV. The only prominent feature at Kew is the "bay" on the *D* curve about 4 p.m., with simultaneous but rather nondescript movements in the *H* curve. This corresponds fairly in time to the large "bay" on the Axelöen *H* curve, representing one of Birkeland's "elementary polar" storms. There is also a "bay" at this same time on the Antarctic *D* curve. The chief movements shown by the Antarctic *V* curve occur later, and are not clearly represented elsewhere.

Fig. 28 for October 28 corresponds to part of Birkeland's Plate V. The Kaafjord curves show two not very

conspicuous "elementary polar" storms, culminating about 6.45 p.m. and 10 p.m. respectively. The Kew curves show "bays" about these times, but they are far

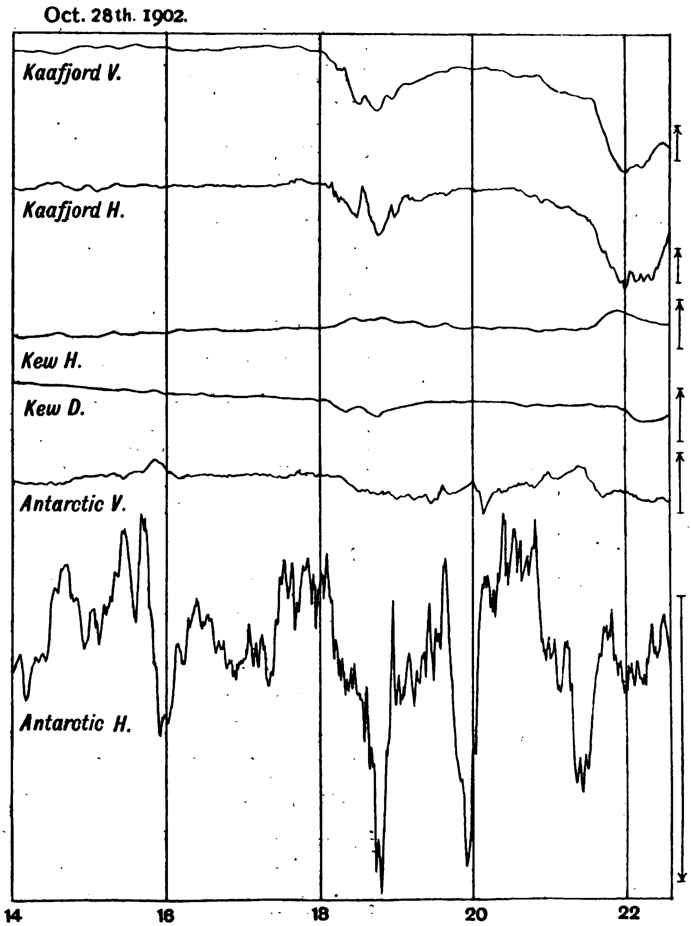


FIG. 28.—ARCTIC-KEW-ANTARCTIC CURVES.

from prominent. The Antarctic curves show considerable disturbance, but its parallelism to that elsewhere is not very obvious.

Fig. 29 for October 30, 1902, corresponds to part of Birkeland's Plate VI. The storm was described by Birkeland as "compound," including both "equatorial" and "polar" storms; during the time covered by Fig. 29 he regarded the "equatorial" disturbance as predominating. The chief movements at Kew and other temperate stations took place between 1 and 2 a.m. They are considerably smaller than the corresponding movements in the Kaafjord and Matotchkin curves, and the latter in their turn are exceeded by the simultaneous movements in the Antarctic. The large "bays" on the Antarctic curves seem to overlap in time the movements seen elsewhere.

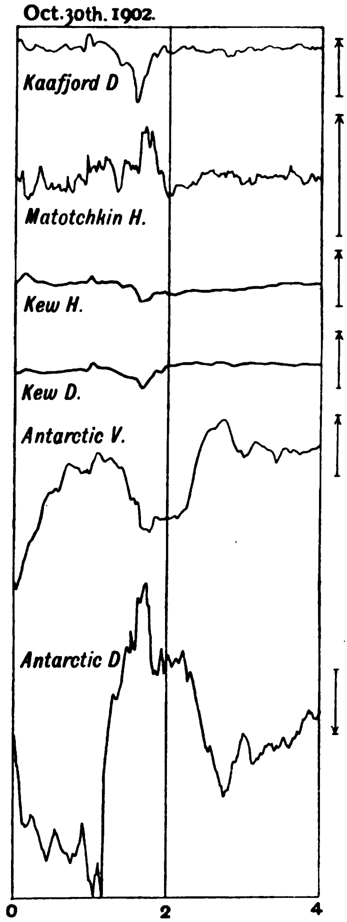


FIG. 29.
ARCTIC-KEW-ANTARCTIC CURVES.

Fig. 30 for October 31, 1902, corresponds to part of Birkeland's Plate VII. He regards the disturbance as on the whole the largest which occurred during his Arctic observations. The earlier part of the disturbance is supposed to be "equatorial," a "polar elementary" storm intervening between 1 and 2 p.m. This "polar" storm is well shown by the Matotchkin H curve. It coincides in time with some of the more marked oscillations in the Kew D and H curves, and with the largest movement in the Antarctic curves. The Kew curves show between 5 and 6 p.m. movements similar in

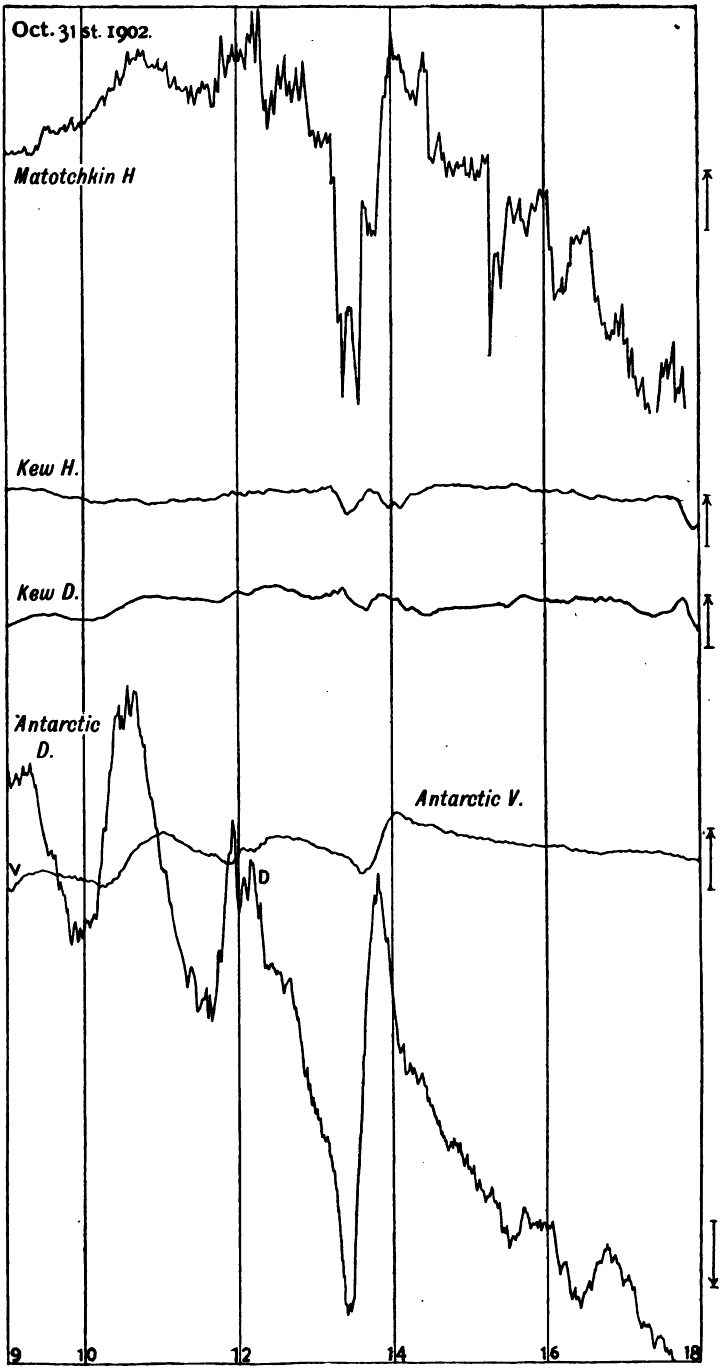


FIG. 30.—ARCTIC-KEW-ANTARCTIC CURVES.

size to those seen earlier. Neither the Arctic nor the Antarctic curves show any specially prominent oscillation at this hour, but a large and comparatively steady movement down the sheet took place in the Matotchkin *H* curve and the Antarctic *D* curve. Prior to noon the Arctic curves were comparatively quiet, and Birkeland was disposed to regard the earlier disturbances as of a different type from the later. The forenoon disturbances, however, in the Antarctic, while much larger than those seen elsewhere, appear to be exactly of the same type as those seen later. If they were "equatorial" disturbances, then "equatorial" disturbances on this occasion were much larger at 77°51′ *S.* than near the equator.

Fig. 31 for November 23, 1902, corresponds to the earlier part of Birkeland's Plate VIII. It extends to about 11.20 p.m., when the sheet was taken off in the Antarctic and the record interrupted for an hour. The storm is described as "compound" by Birkeland, who regarded the disturbance up to 4 p.m. as "equatorial." The principal disturbance, occurring after 10 p.m., he regarded as "polar," and he recognised a smaller "polar" storm culminating between 5 and 6 p.m. Much the largest disturbance seen at Kew and other temperate stations during the time covered by the figure occurred after 10 p.m., contemporaneously with the large "bay" on the Kaafjord *H* curve. The Antarctic *D* and *H* traces went beyond the limits of registration at this time, and judging by the size of the movement in the *V* curve, the conditions must have been highly disturbed. Prior to 10 p.m. the Antarctic curves appear to be considerably more disturbed than the Arctic. They exhibit a particularly rapid oscillation about 3.30 p.m., corresponding to similar but smaller movements at Kew and other temperate and equatorial stations, which Birkeland supposed to be of "equatorial" origin.

Fig. 32 for November 24, 1902, corresponds to all but

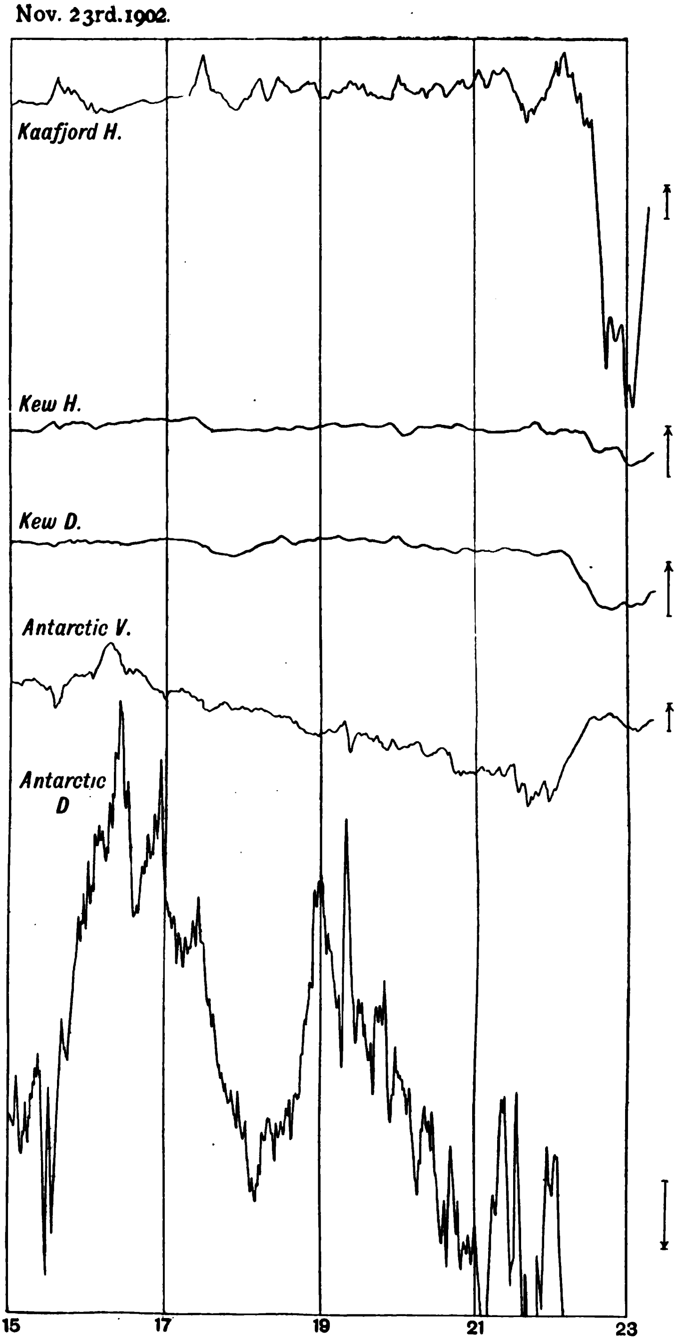


FIG. 31.—ARCTIC-KEW-ANTARCTIC CURVES.

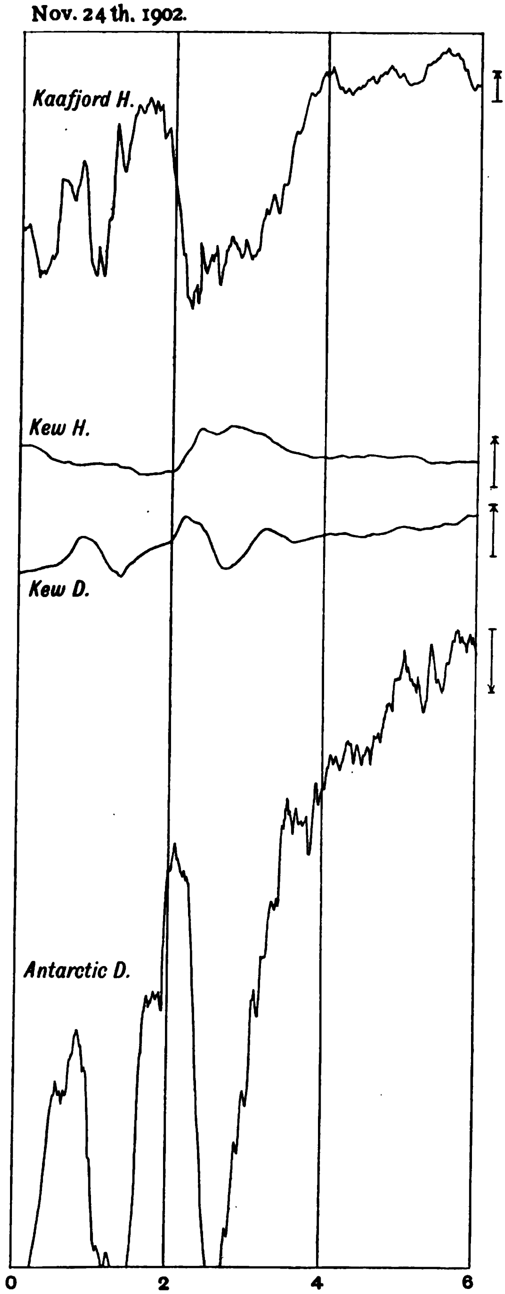


Fig. 32.—Arctic-Kew-Antarctic Curves.

the last hour of the later part of Birkeland's Plate VIII. The disturbance during this time was apparently regarded by Birkeland as a series of "polar elementary" storms. The large "bay" on the Kaafjord *H* trace from a little before 2 to 4 a.m. represents presumably one of these. If the Kew *H* curve during this interval were inverted it would present a considerable resemblance to the Kaafjord curve. The general movement up the sheet in the Antarctic *D* trace is due in part to the regular diurnal variation. If the regular diurnal variation could be eliminated and the trace be completed, it would apparently resemble somewhat closely the Kew *D*

curve. The prominent "bays" between 1 and 2 and between 2 and 3 a.m. must have culminated about the same time as the two largest "bays" on the Kew curve.

Fig. 33 for December 9, 1902, corresponds to the later part of Birkeland's Plate IX. The chief disturbances at Kew consist of a "bay" on the H curve lasting from about 4.30 to 5.40 p.m., and a corresponding oscillation on the D curve. The "bay" corresponds in time to a "bay" on the Dyrafjord H curve—regarded by Birkeland as a "polar elementary" storm—and to a large "bay" on the Antarctic V curve. The Antarctic D curve shows a large oscillation, culminating like that in the Kew D curve shortly after 5 p.m.

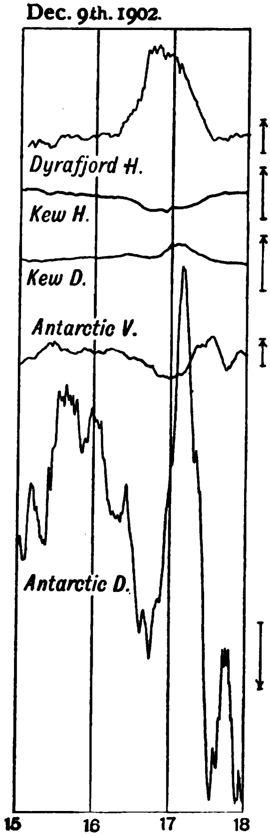


FIG. 33.
ARCTIC-KEW-ANTARCTIC CURVES.

Fig. 34 for December 14 to 15, 1902, corresponds to Birkeland's Plate X. In the Antarctic, registration was interrupted for nearly half an hour about midnight. The disturbance was regarded by Birkeland as a "polar elementary" storm, the culmination of which was markedly earlier at Dyrafjord than at Axelöen. The culmination in the Dyrafjord H curve is near 1 a.m. on the 15th, while that in the Axelöen H curve is about 2 a.m. In the Antarctic, the D curve follows a very similar course to the Dyrafjord curve, having a culminating point shortly after 1 a.m., while the H curve, so far as it exists, presents similar features to the Axelöen H curve. At Kew there are "bays" on the D and H curves, the former the more

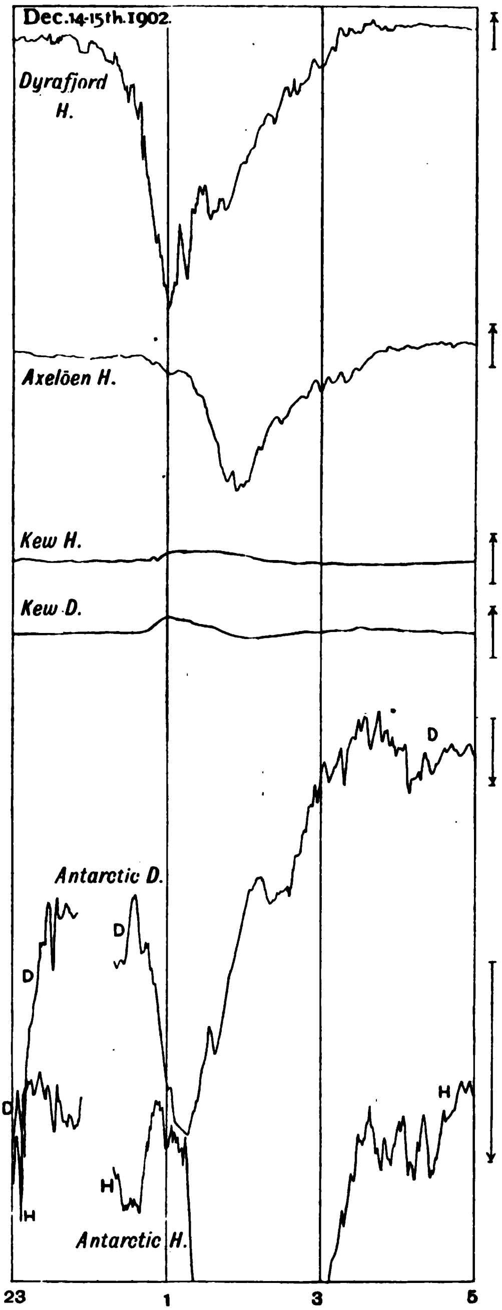


FIG. 34.—ARCTIC-KEW-ANTARCTIC CURVES.

important. The culmination accords in time with that of the Antarctic *D* curve.

Fig. 35 for December 24 to 25, 1902, corresponds to Birkeland's Plate XI. The Antarctic record was interrupted for over half-an-hour between 0 and 1 a.m. on the 25th. The disturbance was regarded by Birkeland as "compound." It was nowhere large. The Kew curves, especially the *D* curve, exhibit small movements between 11 p.m. and midnight on the 24th and between 3 and 4 a.m. on the 25th. The former answers apparently to the "bay" on the Dyrafjord *H* curve, and to those on the Antarctic *V* and *D* curves. The large movement in the Antarctic *D*

curve up the sheet between 1 and 5 a.m. (G.M.T.) represents mainly the regular diurnal inequality, which was at its largest in December. It is the comparatively insignificant "bay" between 3 and 4 a.m., which represents the later movements at Kew and Dyrafjord. Insignificant as it looks, it is considerably larger than the corresponding movement at Kew.

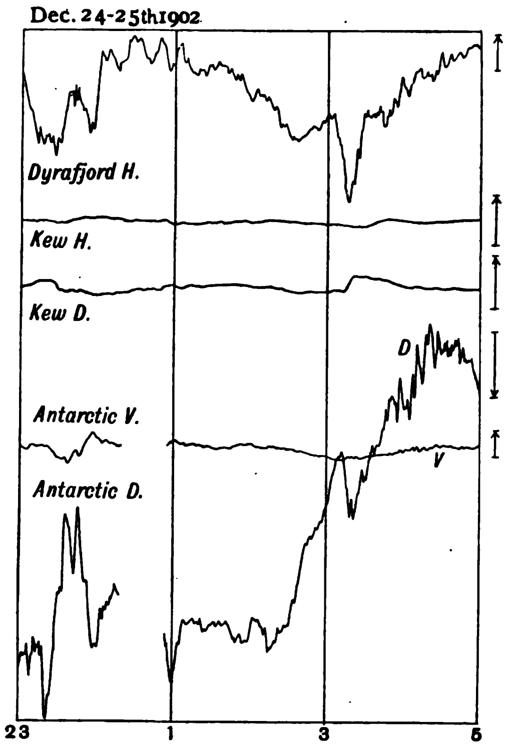


FIG. 35.—ARCTIC-KEW-ANTARCTIC CURVES.

Fig. 36 for December 26 to 27, 1902, corresponds to Birkeland's Plate XII. The Antarctic record was interrupted for about twenty minutes between 11 p.m. and midnight on the 26th. The disturbance was described by Birkeland as consisting in the main of two "polar elementary" storms. Axelöen is the Arctic station which shows the earlier of the two "polar" storms most distinctly. It answers to the "bay" commencing about 8.35 p.m. The extreme positions on the Axelöen curve and the Antarctic *D* curve occur nearly if not quite simultaneously, about 9 p.m. The corresponding movement at Kew is largest in the *D* curve, but the culminating point there occurs somewhat earlier, about the time of occurrence of the earlier of the two peaks on the Antarctic curve. The

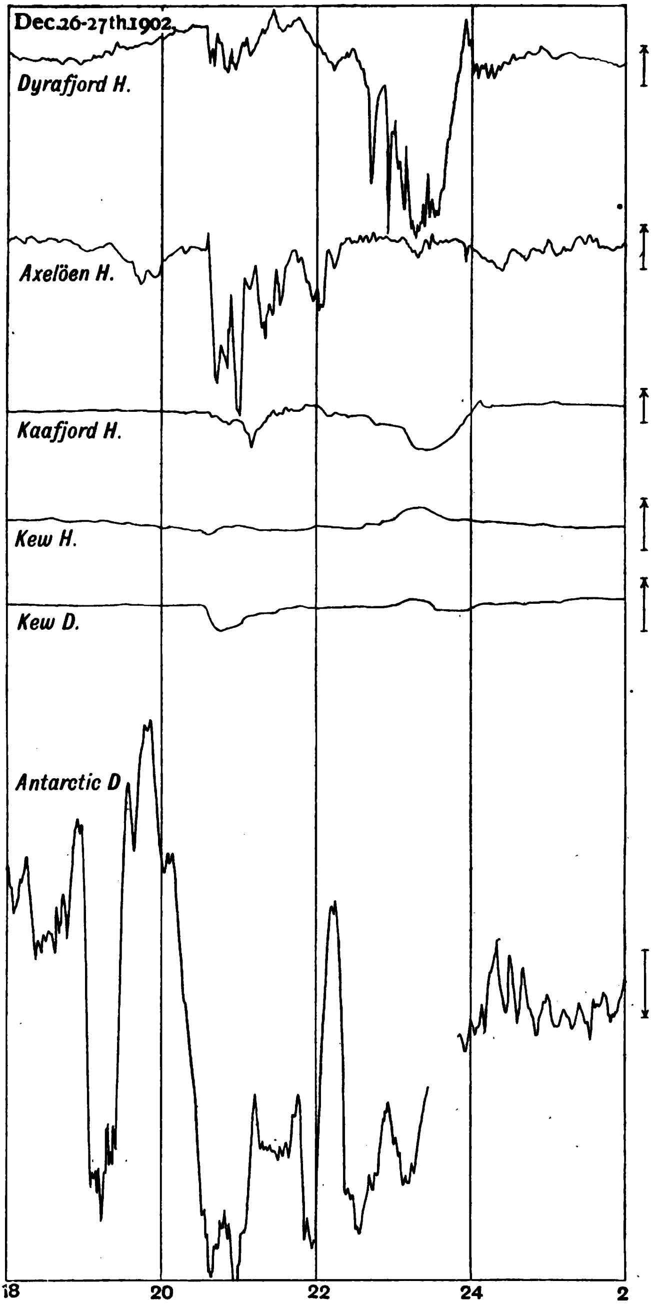


FIG. 36.—ARCTIC-KEW-ANTARCTIC CURVES.

later of the two "polar" storms affected Dyrafjord more than the two other polar stations, and was largest between 10.30 p.m. and midnight. At Kew corresponding to this we have a small "bay" in the *H* curve, and a slow small oscillation on the *D* curve. The Antarctic *D* curve shows a "bay" somewhat overlapping the movements seen elsewhere.

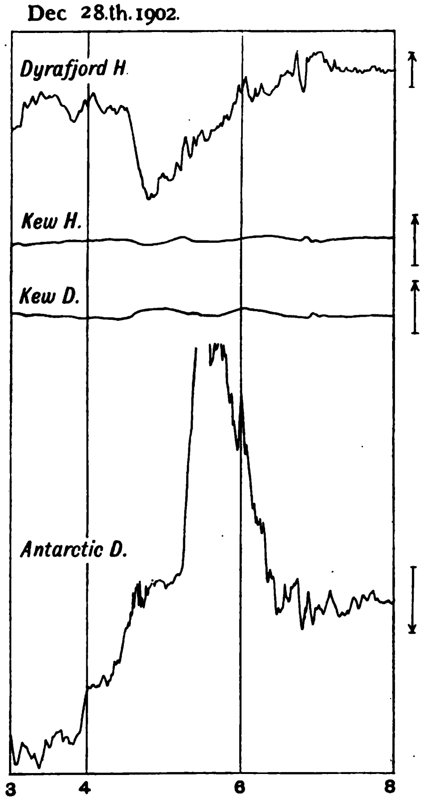


FIG. 37.—ARCTIC-KEW-ANTARCTIC CURVES.

Fig. 37 for December 28, 1902, corresponds to Birkeland's Plate XIII. The storm was classified by Birkeland as "compound," but he regarded its principal feature as a "polar elementary" storm between 4 and 6 a.m., largest at Dyrafjord. Fig. 37 shows well marked "bays" on the Dyrafjord *H* and Antarctic *D* curves, the time of culmination being earlier in the former. The Kew *D* and *H* curves show small, slow oscillations, extending over the times of the Arctic and Antarctic movements. A small rapid oscillation a little before 7 a.m. seems represented in all the traces.

Fig. 38 for February 8, 1903, corresponds to Birkeland's Plate XVI. The Antarctic *H* trace was off the sheet until 9 a.m. The Kew curves were disturbed during the whole time. The chief movement in the Kew *H* curve is a

"bay" culminating about 10 a.m. The Antarctic *H* curve has a large "bay" which must have culminated near 10, though the exact time is unknown owing to the trace going off the sheet. There is a prominent peak in the Axelöen *H* curve which seems to correspond.

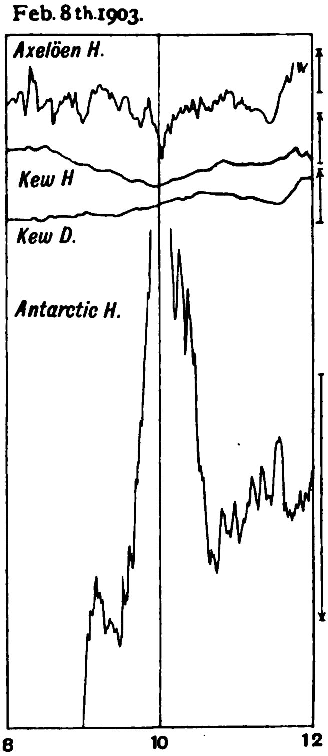


Fig. 38.
Arctic-Kew-Antarctic Curves.

The Antarctic *D* curve was off the sheet most of the time and the working of the *V* magnet was doubtful, so that the *H* trace alone was available.

Fig. 39 for February 8, 1903, answers to the later part of Birkeland's Plate XVII. The disturbance was classified by Birkeland as "compound," but during the time covered by Fig. 39, he believed its principal feature to be a "polar elementary" storm, or succession of "polar elementary" storms, represented by the double "bay" on the Dyrafjord *H* curve, from about 6.30 to 10 p.m. This, it will be seen, presents a somewhat remarkable resemblance to the double "bay" in the Antarctic *D* curve. The principal movements at Kew occurred between 7 and 9 p.m.

Fig. 40 for February 15, 1903, corresponds to Birkeland's Plate XIX. Birkeland classified the disturbance as "compound," while regarding it as in the main of "polar" character. The principal movement in the Axelöen *H* curve is the double "bay" extending from a little after 4 to a little after 6 p.m. This closely resembles the simultaneous double "bay" on the Antarctic

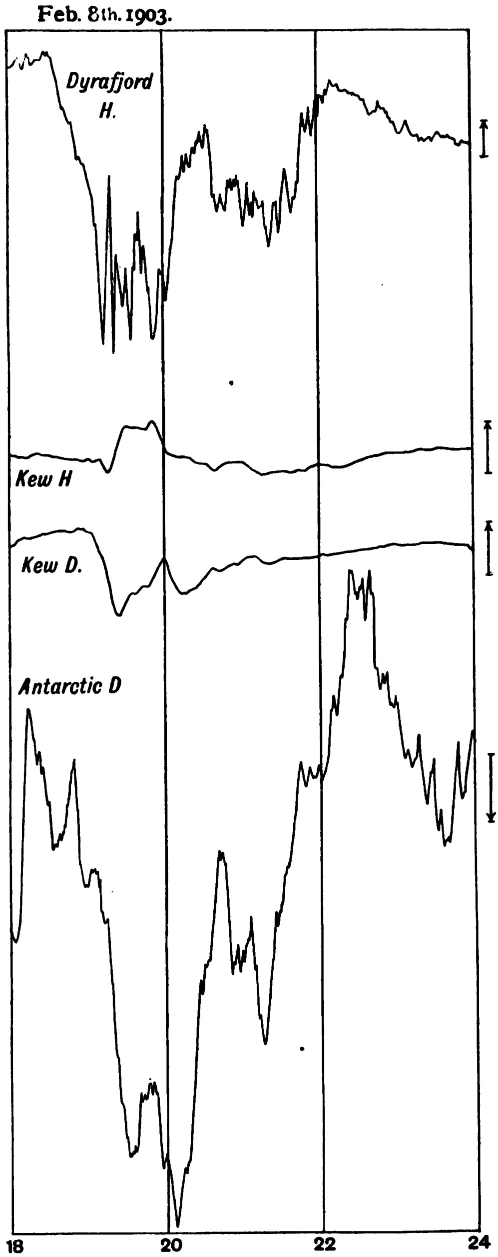


FIG. 39.—ARCTIC-KEW-ANTARCTIC CURVES.

D curve. The principal movements at Kew occurred during this time. The "bay" on the Kew *D* curve seems to answer mainly to the first half of the double "bays" in the Axelöen and Antarctic curves. The second halves of these double "bays" may answer to the second of two "bays" on the Kew *H* curve. If this curve were inverted between 4 and 6 p.m. it would bear a considerable resemblance to the Antarctic *V* curve.

Fig. 41 for March 22, 1903, corresponds to Birkeland's Plate XX. Most of the interval 4 to 6 p.m. has been omitted to bring the figure within the limits of the page. The disturbance was classified by Birkeland amongst his "ele-

mentary polar" storms, on the ground that the principal feature was the "elementary polar" storm seen between 9 p.m. and midnight in Dyrafjord, Axelöen, and Bossekop H curves. This corresponds to a well marked "bay" on the Kew D curve, and there is a conspicuous "bay" corresponding in time on the Antarctic V curve.

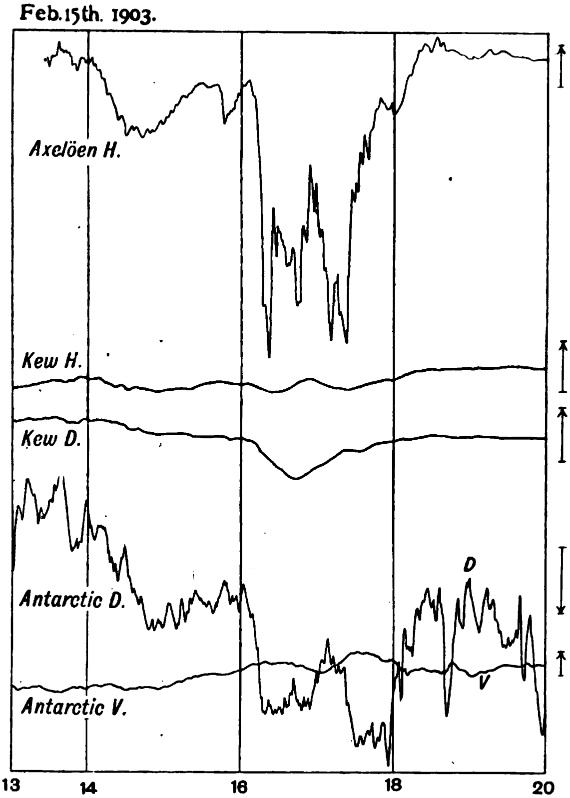


FIG. 40.—ARCTIC-KEW-ANTARCTIC CURVES.

The Antarctic D and H curves show a number of rapid oscillations during this time, but none of an outstanding character. Details are, however, difficult to follow owing to the repeated crossing of the traces. Perhaps the most interesting features are the two sets of oscillations, the earlier a little before 1 p.m., the later about 2.45 p.m. These can be traced readily the

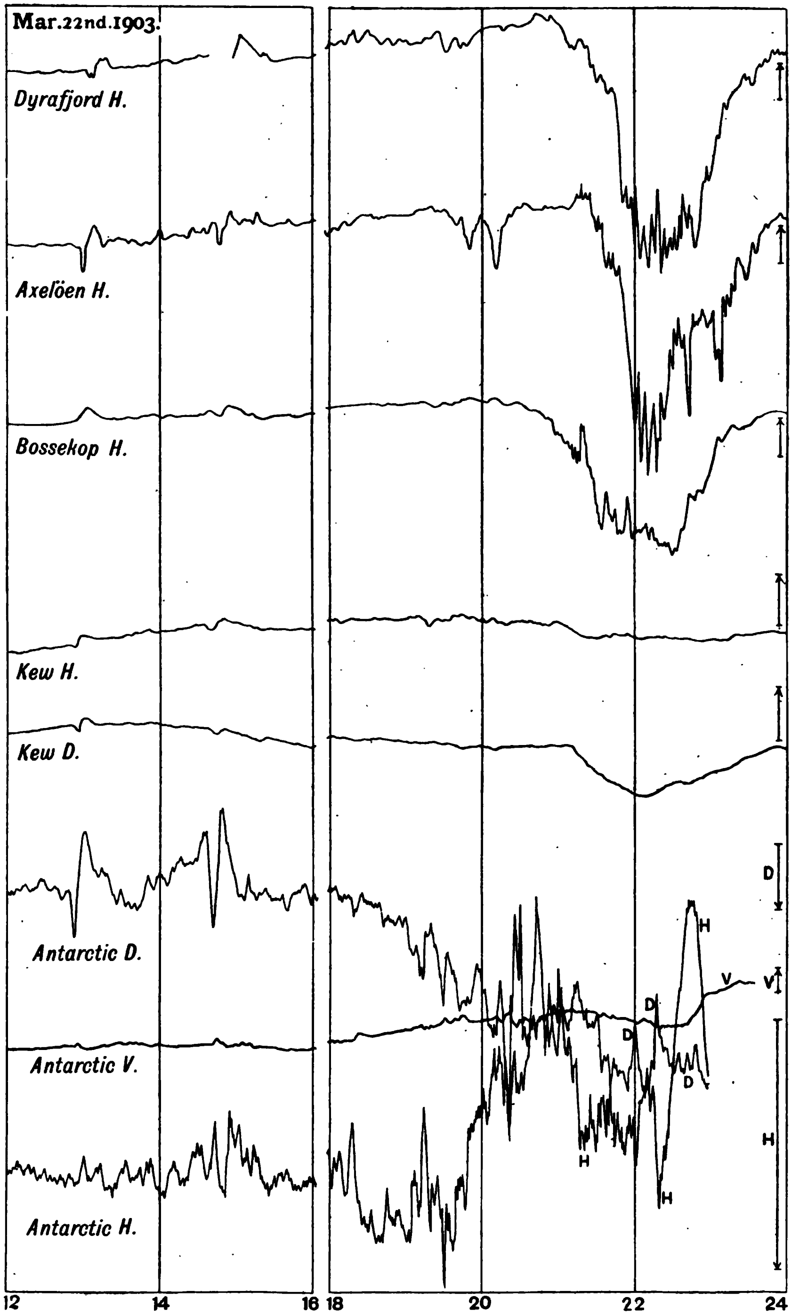


FIG. 41.—ARCTIC-KEW-ANTARCTIC CURVES.

whole way from Axelöen (77°41′N.) to the Antarctic station (77°51′S.). The earlier of the two was noticed by Birkeland, who described it as a "sudden commencement" of an "equatorial" storm. Both sets of movements are at most stations, including Kew, distinctly oscillatory. While distinctly shown in equatorial and temperate latitudes, their chief development is at Axelöen and the Antarctic, the movements in the Antarctic *D* curve being the largest seen anywhere. Thus here again we have a so-called "equatorial" disturbance the chief manifestations of which were in the Antarctic.

Fig. 42 for March 30 to 31, 1903, corresponds to Birkeland's Plate XXI. The disturbance was classified by Birkeland as an "elementary polar" storm, as its chief feature is the "polar" storm shortly after midnight, but he regarded the earlier small movements as an "equatorial" storm. The principal disturbance in the Arctic is represented by the "bays" in the Dyrafjord *V* and *H* curves. It will be observed that the time of their culmination, 1 p.m., does not tally with the culmination of the principal movement seen in the Kew *D* curve, but corresponds to the smaller inverse "bay" on that curve. It tallies, however, with the most prominent peak on the Antarctic *D* curve. The Antarctic *D* curve, moreover, like the Kew *D* curve, has a marked oscillation, and it has a prominent peak about 0·30 a.m. which answers apparently to the chief turning point on the Kew curve.

Some of the earlier movements, though small, appear to be recognisable at all Birkeland's co-operating stations. The most distinct of these is an oscillation about 7.25 p.m., readily recognisable in the Dyrafjord, Kew and Antarctic curves. An almost exactly similar movement, occurring about one hour fifty minutes earlier, is recognisable in the Kew and Antarctic curves (Birkeland's traces do not extend to this time). This apparent

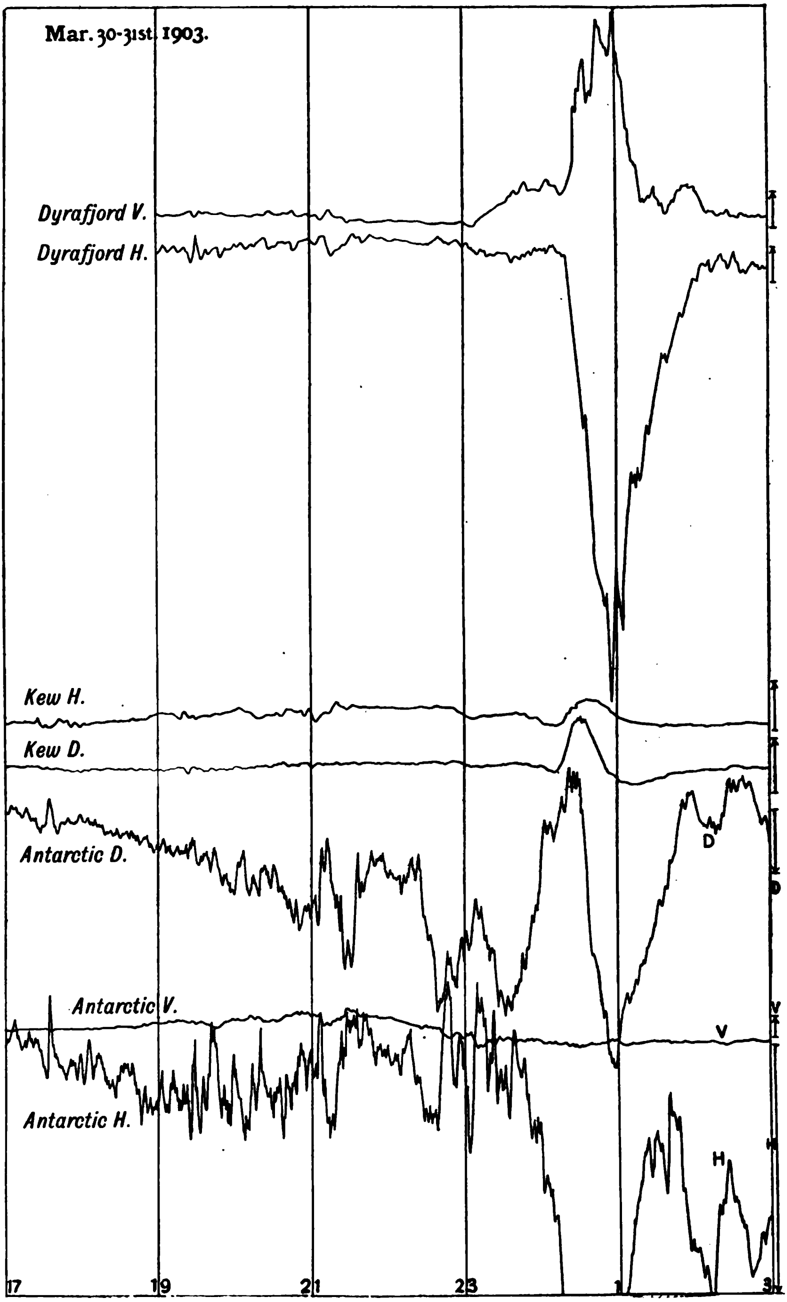


FIG. 42.—ARCTIC-KEW-ANTARCTIC CURVES.

"repetition" on March 31 presents very similar features to the "repetition" already referred to on March 22.

Disturbed conditions being practically chronic in high latitudes, whether northern or southern, it was inevitable that the Antarctic curves would show sensible disturbance during the disturbances shown by the curves of Birkeland's Arctic stations. To establish any real connection, it is necessary to show that more than ordinarily disturbed conditions tend to prevail simultaneously in the Arctic and the Antarctic. It can hardly be claimed that the times indicated on the two sets of curves are of such accuracy as to justify the positive assertion that prominent peaks in them answer to absolutely identical times. Our examination, however, of Figs. 25 to 42 has shown that in a number of cases when conspicuous isolated movements presented themselves in the Arctic curves, conspicuous isolated movements also presented themselves in the Antarctic curves, the time difference between the two events being if not zero at least too small to be measured. This, taken in conjunction with the fact that sudden movements to all appearance simultaneous could be recognised at all the intermediate stations, is at least very strong evidence of a fundamental connection between the phenomena in north and south. In the case of the longer period disturbances described by Birkeland as "polar elementary" storms, prominent "bays" were almost always visible in the Antarctic as well as in the Arctic curves, and the times of largest departure from the undisturbed value were usually closely similar. There seem to be altogether too many coincidences to be assigned to chance.

The disturbances on Birkeland's list were all of a comparatively trifling character except in high latitudes, and no really large disturbance occurred in temperate latitudes while the *Discovery* magnetographs were in operation. Thus neither the Arctic nor the Antarctic 1902–3 curves

tell us what happens in high latitudes during really large magnetic storms in temperate and equatorial latitudes. What they do tell us is that ordinary small disturbances in mean and low latitudes are, at least usually, accompanied by larger disturbances in high latitudes, both northern and southern. The amplitude in high latitudes, as compared with that in mean and low latitudes, seems to be much greater in the case of slowly developing "bay" like movements than in that of comparatively rapid changes similar to those known as "sudden commencements." The short period movements seem to be conspicuously more oscillatory in character in high latitudes than elsewhere. Not improbably the normal type everywhere is oscillatory, the second movement being the longer and larger; but if this be the case, the first movement in mean and low latitudes must frequently be invisible in the ordinary magnetic curve.

The apparent simultaneity of magnetic disturbances everywhere seems at first sight inconsistent with a diurnal variation in the frequency of occurrence of magnetic disturbances at an individual station, while there is undoubtedly somewhat strong evidence in favour of the reality of such variations. For instance, Mr. E. W. Maunder's[1] times of beginnings and endings of some 720 disturbances recorded at Greenwich between 1848 and 1903 lead to the results given in Table LII.

TABLE LII.—*Magnetic Storms at Greenwich.*

—	Percentages of occurrences.		
	1—8 p.m.	9 p.m. to 4 a.m.	5 a.m. to noon.
Beginnings	60·1	21·9	18·0
Endings...	9·4	44·6	46·0

When consideration is confined to storms having a

[1] R. A. S. Notices 65, pp. 2 and 538.

sudden commencement, the eight hours ending with 8 p.m. occupy a somewhat less conspicuous but still quite outstanding position.

A possible explanation is that it is really the amplitude and not the frequency of disturbances of a particular type that has a diurnal variation. A "bay" in the Kew *D* curve, for instance, might arise from an atmospheric electric current concentrated in any longitude whatever, but be much larger *ceteris paribus* when the longitude of the current lay between 20E. and 20W. than when it lay between 160W. and 160E. If this were the case, "bays" sufficiently prominent to catch the eye would naturally enough be much more common at one hour G.M.T. than another. The more restricted the area of the electric current tended to be, the more marked would be the diurnal variation of the corresponding type of disturbance. The difference between the relative amplitudes in mean and high latitudes of the disturbances regarded by Birkeland as "equatorial" and "polar" may mean not that there are, as he supposes, overhead currents in equatorial regions in the one case and in polar regions in the other, but simply that the overhead currents while mainly polar in both cases are of less local distribution—possibly also at a greater altitude—in the case of the "equatorial" than in that of the "polar" disturbances.

Our discussion of magnetic disturbances will have shown that complicated as these phenomena are, a certain amount of order has been already detected in their manifestations. At Kew, for instance, we know that large disturbances are most common in the equinoctial and least common in the summer months. In the case of "sudden commencements," the horizontal force is the element which usually is principally affected, and if we take the value of that element five minutes after the disturbance has commenced we shall nearly always find it higher than the undisturbed value. This rise is, at least sometimes,

preceded by a relatively small and short lived decrease, and an oscillation is sometimes distinctly visible in the declination trace when it is not visible in that of the horizontal force. At the end of any large storm the horizontal force is usually depressed, and a rapid recovery is generally in progress during the next day or two.

"Bays" on the declination traces, sufficiently large to catch the eye, are most usual in the afternoon, and the displacement of the magnet is then usually to the east of its normal position.

When the vertical force experiences a disturbance which is not of a rapidly oscillatory character, the force is nearly always increased when the disturbance occurs in the afternoon up to 8 or 9 p.m., while it is generally diminished when the disturbance occurs in the early morning.

The vertical force changes are usually of a much less oscillatory character than those in the horizontal components, and it is not unusual for the vertical force trace to appear quite regular while the declination and horizontal force traces are full of sinuosities.

In the Antarctic the phenomena differ in many respects from those at Kew. Summer and not equinox seems the season when disturbances are largest and most numerous. "Sudden commencements" seem always of an oscillatory character, and, speaking generally, a tendency to oscillation and continual unrest is one of the most outstanding features.

It is to investigations of how the phenomena at different parts of the earth are related, and how they depend on the time of day, on the season of the year, and on sunspot frequency, that, I think, we must look as the most hopeful way of advancing knowledge.

CHAPTER XIV

SUNSPOTS AND TERRESTRIAL MAGNETISM

In public estimation the man who professes a belief in sunspot influence upon the earth is suspect; and in some individual instances there have been grounds for suspicion. In the case of the ordinary meteorological elements, the question as to whether there is an eleven-year period is one on which equally competent authorities might hold different views. In the case of Terrestrial Magnetism, different views may be held as to the nature of the relationship, but that a relationship exists between sunspot frequency and the range of the regular diurnal inequality is the common belief of magneticians. So far as is known, the inequality range is above the mean, the whole earth over, in years of many sunspots, and the excess is conspicuous in years when sunspot frequency is largest.

Table LIII. contrasts the mean diurnal inequality for the year at Kew from two groups of years, viz., 1892–95 with a mean sunspot frequency [1] of 75·0, and 1890, 1899, and 1900, with a mean sunspot frequency of 9·6.

For brevity the two groups are described as years of sunspot maximum (S. max.) and sunspot minimum (S. min.). Ordinary (*o*) and quiet (*q*) day results are both given for *D*, but only quiet day results for the other elements. The extreme hourly values are in heavy type. The table

[1] Here and elsewhere in this book the values assigned to sunspot frequency are those published by Prof. Wolfer, of Zurich.

gives also the range deduced from the hourly values, and the average departure from the mean. For the force elements the unit employed is $0{\cdot}1\gamma$.

TABLE LIII.—*Kew Diurnal Inequalities in Years of Many and Few Sunspots.*

Hour.	Declination.				Horizontal Force.		West Component.		North Component.	
	o.		*q.*							
	S max.	S. min.	S. max.	S. min.	S. max.	S. min.	S. max.	S. min.	S. max.	S. min.
1	−1′·84	−1·08	−1′·12	−0′·63	+53	+33	−41	−22	+68	+41
2	−1·90	1·01	−1·18	−0·63	+49	+26	−45	−24	+65	+35
3	−1·98	−1·08	−1·30	−0·76	+48	+30	−52	−30	+66	+41
4	−2·17	−1·29	−1·60	−1·02	+50	+30	−66	−43	+73	+45
5	−2·54	−1·62	−2·18	−1·45	+53	+32	−95	−64	+85	+53
6	−2·93	−1·92	−2·86	−1·88	+35	+15	−135	−91	+79	+44
7	−3·23	−2·21	−3·39	−2·32	−6	−10	−174	−121	+48	+27
8	−**3·31**	−**2·31**	−**3·68**	−**2·56**	−77	−56	−**210**	−**147**	−15	−13
9	−2·57	−1·75	−3·06	−2·05	−161	−109	−203	−137	−105	−72
10	−0·44	−0·16	−0·98	−0·48	−222	−**142**	−116	−67	−197	−128
11	+2·42	+1·96	+1·83	+1·61	−**225**	−136	+26	+41	−**244**	−**155**
Noon	+4·97	+3·78	+4·45	+3·49	−168	−86	+176	+152	−231	−137
1	+**6·13**	+**4·44**	+**5·69**	+**4·15**	−100	−32	+**259**	+**201**	−185	−96
2	+5·91	+3·93	+5·31	+3·54	−39	+4	+258	+181	−121	−52
3	+4·62	+2·75	+3·98	+2·28	+7	+20	+204	+122	−56	−17
4	+3·05	+1·58	+2·36	+1·13	+34	+21	+130	+64	−5	+2
5	+1·64	+0·71	+1·09	+0·38	+63	+32	+74	+29	+43	+25
6	+0·65	+0·17	+0·39	0·00	+91	+48	+47	+14	+81	+46
7	−0·06	−0·20	0·00	−0·18	+**104**	+**63**	+31	+9	+99	+**63**
8	−0·62	−0·53	−0·35	−0·34	+100	+56	+12	0	+**101**	+59
9	−1·06	−0·84	−0·60	−0·47	+93	+50	−3	−9	+98	+55
10	−1·37	−1·05	−0·71	−0·54	+79	+40	−13	−15	+87	+47
11	−1·61	−1·15	−0·95	−0·59	+76	+38	−26	−19	+87	+46
12	−1·77	−1·14	−1·14	−0·67	+64	+35	−37	−24	+79	+44
Range...	9·44	6·75	9·37	6·71	329	205	469	348	345	218
Average departure	2·45	1·61	2·09	1·38	83	48	101	68	97	56

The excess in the sunspot maximum years is substantial in the range, and is even more marked in the average departure from the mean. This obviously implies a change in the type as well as in the amplitude of the inequality. More minute examination of the data, or of ordinary inequality curves embodying them, shows that

the difference in type between the years of many and few sunspots exists mainly between 7 p.m. and 9 a.m., and so during the hours when the regular diurnal changes are least conspicuous.

Fig. 43 gives the vector diagrams in the horizontal plane for the mean diurnal inequality for the year from quiet days at Kew, in the sunspot maximum and sunspot minimum groups of years. They are drawn to one scale from a common origin. The arms of the cross formed by the co-ordinate axes represent each 10γ. The mean magnetic meridians were not absolutely identical for the two groups of years, but their inclination is too small to be shown in a figure of the size. The radius vector to *M* shows their position. The diagram for sunspot minimum years lies wholly inside the other, and is as it were slightly twisted round. The twist arises from the fact that in the afternoon hours the sunspot minimum vector is ahead of the other. The sunspot maximum diagram is decidedly smoother than the sunspot minimum diagram, and is more rounded during the night hours.

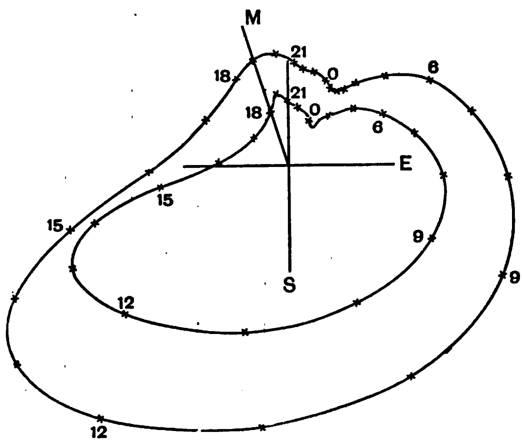


FIG. 43.—Kew Vector Diagrams.

Table LIV. contrasts the ranges of the diurnal inequalities of declination for the twelve months of the year derived from years of many and years of few sunspots at several stations. The nature of the day whether "all," "ordinary," or "quiet," is denoted by the usual letters *a*, *o*, *q*.

TABLE LIV.—*Diurnal Inequality Ranges in Years of Many and of Few Sunspots.*

Month.	Kew (o).		Falmouth (q).		Pavlovsk (a).		Pavlovsk (q).		Katharinen-burg (a).	
	S. max.	S. min.	S. max.	S. min.	S. max.	S. min.	S. max.	S. min.	S. max.	S. min.
	′	′	′	′	′	′	′	′	′	′
January ..	5·63	4·17	5·06	3·37	5·36	4·12	3·83	2·27	3·54	3·16
February.	7·61	4·77	6·71	3·77	7·58	4·89	6·07	2·83	5·14	3·17
March ...	10·64	7·54	10·74	7·26	10·23	7·00	10·72	7·30	8·98	6·16
April ...	12·96	9·25	12·27	9·20	12·81	9·51	13·10	9·83	13·08	9·78
May ...	12·57	8·80	11·99	8·32	14·54	10·09	15·60	10·60	13·74	9·97
June ...	13·05	9·73	12·42	8·59	14·77	10·52	15·25	11·47	13·66	9·72
July ...	12·42	8·73	12·18	8·80	13·59	10·11	14·13	10·47	12·69	9·68
August ...	12·65	9·56	12·79	8·93	13·01	10·18	13·67	10·20	12·04	9·33
September	10·94	8·39	11·48	7·90	9·46	7·46	10·20	8·10	8·98	7·05
October...	8·96	6·59	8·70	6·47	8·24	5·22	8·37	6·30	6·62	4·75
November	6·08	4·40	6·01	3·85	6·79	4·09	4·55	2·90	4·30	2·95
December	5·39	3·62	4·26	2·24	5·15	3·75	3·47	2·07	3·50	2·70
Year ...	9·44	6·75	9·47	6·25	8·80	6·18	9·48	6·70	7·92	5·68

In all cases the sunspot maximum years were 1892–95 (mean frequency 75·0), and the sunspot minimum years, except at Falmouth, were 1890, 1899 and 1900 (mean frequency 9·6). At Falmouth sunspot minimum comprised the four years 1899 to 1902 (mean frequency 7·3). At Kew and Falmouth the years in each group were combined so as to get a single inequality for each of the twelve months. At Pavlovsk and Katharinenburg the years were treated separately, the monthly values in the table representing arithmetic means of the ranges for the months of the same name. The values assigned to the year represent the ranges in the mean diurnal inequality for the year, all the years of the group being combined at Kew and Falmouth to give a single inequality, while arithmetic means of individual year's results are taken for Pavlovsk and Katharinenburg.

At Pavlovsk on quiet days the arithmetic mean of the ranges for the four midsummer months bears to the corresponding mean for the four midwinter months a ratio which is 4·2 in years of sunspot minimum, as

against 3·3 in years of sunspot maximum. From a *relative* point of view, winter and summer in years of sunspot maximum are brought nearer together.

Table LV. contrasts the amplitude of the 24-hour Fourier term for the diurnal inequality in years of many and of few sunspots. The groups of sunspot maximum and minimum years in this and subsequent tables are the same as those employed for the same stations in Table LIV. In all cases the winter value is a larger fraction of the summer value in years of many than in years of few sunspots. The amplitude of the 24-hour term thus follows the same law as the amplitude of the diurnal inequality itself.

TABLE LV.—*Amplitude of 24-hour term in Years of Many and Few Sunspots.*

—	Kew *D.*				Falmouth *D.*		Falmouth *H.*	
Season.	*o.*		*q.*		*q.*		*q.*	
	S. max.	S. min.	S. max.	S. min.	S. max.	S. min.	S. max.	S. min.
	′	′	′	′	′	′	γ	γ
Year	3·47	2·21	2·86	1·80	2·74	1·57	13·9	7·6
Winter	2·42	1·43	1·83	0·99	1·86	0·78	7·4	2·8
Equinox...	3·76	2·41	2·99	1·98	2·84	1·77	15·1	8·9
Summer	4·38	2·98	3·85	2·56	3·62	2·30	20·4	11·7

Table LVI. shows how the amplitudes of the 12-, 8-, and 6-hour terms in the mean diurnal inequality for

TABLE LVI.—*Ratios of Fourier Waves in Years of Many and Few Sunspots.*

Element.	Place.	c_2/c_1.		c_3/c_1.		c_4/c_1.	
		S. max.	S. min.	S. max.	S. min.	S. max.	S. min.
D.	Kew	0·74	0·86	0·35	0·44	0·10	0·16
	Falmouth ...	0·79	0·99	0·38	0·51	0·11	0·17
H.	Kew	0·54	0·58	0·23	0·31	0·11	0·19
	Falmouth ...	0·53	0·54	0·20	0·28	0·09	0·15

the year (in quiet days) stand to that of the 24-hour term in years of many and of few sunspots. The importance of the shorter period terms relative to the 24-hour term diminishes in all cases as sunspot frequency increases.

Table LVII. gives the algebraic excess of the phase angles for the mean diurnal inequality of the year (from quiet days) in sunspot minimum as compared with sunspot maximum years at Kew (K) and Falmouth (F).

TABLE LVII.—*Difference of Phase Angles in Years of Many and Few Sunspots.*

	D.				*H.*				*W.*				*N.*			
	K.		*F.*		*K.*		*F.*		*K.*		*F.*		*K.*		*F.*	
	°	′	°	′	°	′	°	′	°	′	°	′	°	′	°	′
a_1	3	13	3	57	4	46	2	55	4	42	4	36	2	47	2	32
a_2	6	36	4	28	13	57	8	0	8	25	7	10	7	58	1	57
a_3	7	4	2	56	14	29	10	47	7	51	3	44	12	37	8	28
a_4	7	12	0	29	−4	32	0	9	5	2	0	9	−7	57	1	15

The sunspot minimum angle is the larger in all cases but two, both relating to the 6-hour term. In this term, from the point of view of the time equivalent, the difference is much less than in the 24-hour term.

The difference between the phase angles in years of sunspot maximum and minimum varies with the season of the year. This is illustrated by the data for Kew declination from quiet and from ordinary days given in Table LVIII.; differences in phase angles are expressed in minutes of *time*. The results are arithmetic means from the individual months belonging to the season.

TABLE LVIII.—*Retardation of Phase (in minutes of time) in Years of Sunspot Maximum. (Declination at Kew).*

Season.	Year.		Winter.		Equinox.		Summer.	
Term.	*q.*	*o.*	*q.*	*o.*	*q.*	*o.*	*q.*	*o.*
24-hour ...	24·0	23·5	54·9	52·3	13·5	9·7	3·7	8·3
12-hour ..	15·8	12·8	27·7	28·2	10·7	6·2	9·0	3·9

In summer, on ordinary days, the maximum of the 24-hour wave is only 8·3 minutes earlier in the day in years of sunspot minimum than in years of sunspot maximum, but in winter this difference rises to 52·3 minutes. The difference seems even more marked on quiet days. Except in summer the difference in time represented by the difference in phase between years of sunspot maximum and minimum is decidedly less for the 12-hour than the 24-hour term.

Table LIX. contrasts the results obtained in years of many and few sunspots at Kew and Falmouth, for the annual and semi-annual terms in the annual variation of diurnal inequality. The letters o and q have their usual meaning. Results are given for the amplitude of the 24-hour term as well as for the average departure from the mean. M, P_1, and P_2 have the same meanings as in Table XXVI, p. 81.

In every case P_1/M shows a marked increase as we pass from sunspot maximum to minimum.

TABLE LIX.—*Annual Variation in Years of Many and Few Sunspots.*

	Average departure.			c_1.		
	P_1/M.	P_2/M.	P_2/P_1.	P_1/M.	P_2/M.	P_2/P_1.
Kew D (o). S. max.	0·330	0·113	0·34	0·339	0·083	0·25
,, ,, S. min.	0·408	0·110	0·27	0·411	0·080	0·20
,, D (q). S. max.	0·391	0·088	0·23	0·422	0·063	0·15
,, ,, S. min.	0·490	0·101	0·21	0·519	0·063	0·12
Falmouth D (q). S. max.	0·35	0·10	0·28	0·39	0·06	0·15
,, ,, S. min.	0·48	0·14	0·28	0·56	0·09	0·17
,, H (q). S. max.	0·46	0·07	0·15	0·54	0·08	0·15
,, ,, S. min.	0·54	0·15	0·28	0·67	0·16	0·24

Table LX. exhibits the differences between the sunspot maximum and sunspot minimum values of the phase angles in the annual and semi-annual terms, expressed in

days. The quiet day results are means derived from the range, the average departure from the mean and c_1; the ordinary day results are derived from the two latter quantities only. A plus sign denotes an earlier occurrence of the maximum of the term in the sunspot maximum years. The close resemblance between the Kew and Falmouth results for the annual term is noteworthy.

TABLE LX.—*Difference, in Days, in Times of Occurrence of Maxima in Years of Sunspot Maximum and Minimum (+ denotes earlier occurrence at sunspot maximum).*

	Annual Term.		Semi-Annual Term.	
	D.	*H.*	*D.*	*H.*
Falmouth (*q*) ...	+3·5	+11·1	+6·4	+4·3
Kew (*q*)...	+3·4	+10·3	+7·0	−3·1
Kew (*o*)	+8·9	—	−5·3	—

CHAPTER XV

WOLF'S SUNSPOT FORMULA

THE nature of the relation between sunspot frequency and the amplitude of the diurnal inequality has been investigated graphically and algebraically. In the graphical method—which was applied by Mr. W. Ellis, F.R.S.,[1] to the long series of magnetic data existent for Greenwich—two curves are drawn having a common time axis of abscissæ, the ordinates representing sunspot frequency in the one curve and magnetic range in the other. The second method, due originally to Prof. Wolf, of Zurich, assumes magnetic range R and sunspot frequency S to be connected by a linear relation

$$R = a + bS \quad . \quad . \quad . \quad . \quad (1).$$

Here a and b are constants to be determined from the observed values of R and S by least squares or other suitable method. Wolf's formula can, of course, be justified only by an accordance with observation. Its value must also depend to some extent on whether the results deduced for a and b from different series of years are in close accord or not.

In 1903 it occurred to me to try whether Wolf's formula could be applied to the individual months of the year. The formula proved to be fairly applicable to the different months, only b/a was found to vary with the season, and not merely the absolute values of a and b.

[1] *Phil. Trans.*, **171**, p. 541; *Roy. Soc. Proc.*, **63**, p. 64.

To demonstrate the extent of this variability, it is convenient to write m for b/a, thus replacing (1) by

$$R = a(1 + mS) \quad . \quad . \quad . \quad . \quad (2).$$

Table LXI. gives the values calculated for a and $100m$ at Kew from the quiet days of the eleven years 1890 to 1900. The value assigned to a for any season is really the arithmetic mean of the values obtained for the individual months comprised in the season. Corresponding mean values were obtained for b, and the values assigned to m in the table were calculated from these mean a's and b's. The monthly values of a and b were calculated by least squares.

TABLE LXI.—*Values of Constants in Formula* (2), *for Quiet Days at Kew.*

Season.	*D.*		*I.*		*H.*		*V.*	
	a.	100*m.*	*a.*	100*m.*	*a.*	100*m.*	*a.*	100*m.*
	′		′		γ		γ	
Year	6·49	0·63	1·17	1·11	21·5	0·89	16·0	0·45
Winter	3·23	1·00	0·63	1·66	10·5	1·45	7·0	0·71
Equinox	7·32	0·65	1·26	1·17	23·5	0·94	17·5	0·41
Summer	8·91	0·48	1·61	0·85	30·6	0·62	23·5	0·39

Values obtained for a and b for individual months of the year, even when calculated by least squares, have rather a large probable error, at least for so short a period as eleven years, and the arithmetic mean of the m's obtained for the four months of, say, winter would be exposed to a considerably greater accidental error than the value obtained by the method actually employed.

It is obvious from (2) that a is the value of R when S vanishes, and so is the ideal range for a total absence of sunspots. If the range of an element in the absence of sunspots be regarded as unity, then $100m$ is the increase in the range answering to a sunspot frequency of 100. Taking, for example, the year as a whole, in the case of D the fact that $100m$ equals 0·63 signifies that the range

when sunspot frequency is 100 is 63 per cent. larger than when there are no sunspots.

It will be noticed that m is notably largest in winter in all the elements. From one point of view this only confirms the conclusion reached when discussing Table LIV., p. 163, viz., that relatively considered the increase of the range of the regular diurnal inequality with sunspot frequency is greatest in winter; but the result being now numerical becomes more definite. The seasonal variations in m at Kew are fairly similar in the different elements. Taking a mean from the four elements, we find the values of m in winter, equinox and summer to stand to one another roughly as 6 : 4 : 3. The absolute values, however, of m in Table LXI. differ notably for the different elements, being roughly as 5 : 4 : 3 : 2 for I, H, D and V respectively.

During the eleven years 1890 to 1900, S varied from 0·6 to 129·2 in individual months, and from 7·1 to 84·9 in individual years. This will give some idea of the great variability to be expected in the range of the regular diurnal inequality. Sunspot frequency was by no means exceptionally variable between 1890 and 1900. Some eleven-year periods have shown much larger fluctuations. For instance, the mean yearly value of S varied from 139·1 in 1870 to only 3·4 in 1878. The sunspot frequency of 1870 was the largest of last century. It was, however, considerably exceeded in 1778, when the mean value reached 154·4, after having been only 7·0 in 1775. These figures taken in conjunction with Table LXI. will show the importance, when comparing stations, of employing the same years, or years having closely similar sunspot frequencies.

Table LXII. gives values of m, or rather of $100m$, derived from arithmetic mean values of a and b exactly as in Table LXI. The values of a and b themselves were obtained, however, in a simpler way. To explain this,

take the case of the range of the diurnal inequality of declination at Kew in the month of January. The diurnal inequality derived from the Januarys of the four years of sunspot maximum 1892–5 combined had a range of $4'{\cdot}97$, while that derived from the Januarys of the three years of sunspot minimum, 1890, 1899 and 1900 combined, had a range of $3'{\cdot}26$. The corresponding sunspot frequencies in the two cases were respectively 72·65 and 11·40. Thus by (1):

$$a + b \times 72{\cdot}65 = 4{\cdot}97,$$
$$a + b \times 11{\cdot}40 = 3{\cdot}26;$$

whence

$$b = 1{\cdot}71 \div 61{\cdot}25 = 279 \times 10^{-4}.$$

A value might also be found for a from these equations. But it is better to derive it from the fact that the diurnal inequality for the Januarys of the eleven years combined had a range of $4'{\cdot}07$, the corresponding sunspot frequency being 39·8. According to (1) we have

$$a + b \times 39{\cdot}8 = 4{\cdot}07.$$

Assigning to b the value 279×10^{-4} obtained above, we deduce $a = 2{\cdot}96$.

This method is not to be recommended unless the years of sunspot maximum and minimum stand out well from the intermediate years.

The letters o and q in Table LXII. have their usual sense. K denotes Kew, and F Falmouth. The periods employed were 1890 to 1900 for the former station, and 1891 to 1902 for the latter. Wolf's formula was applied to the average departure from the mean as well as to the range, the procedure in the two cases being the same.

The quiet day results for the Kew ranges in Table LXII. are not identical with those in Table LXI., which were obtained by least squares, but there is a good general agreement. The parallelism between the Kew and Falmouth quiet day results in Table LXII. is also

satisfactory. It shows that the seasonal variation in m is not peculiar to Kew.

TABLE LXII.—*Values of* 10^2m *derived from Groups of Years.*

Season.	Range.					Average departure from mean.				
	D.			*H.*		*D.*			*H.*	
	K (*o*).	*K* (*q*).	*F* (*q*).	*K* (*q*).	*F* (*q*).	*K* (*o*).	*K* (*q*).	*F* (*q*).	*K* (*q*).	*F* (*q*).
Year	0·67	0·68	0·73	1·00	1·13	0·94	0·85	1·00	1·24	1·35
Winter	0·76	0·93	1·09	1·77	1·96	1·19	1·44	1·88	2·85	2·33
Equinox ...	0·72	0·69	0·76	1·02	1·04	1·03	0·88	0·99	1·20	1·30
Summer ...	0·54	0·59	0·57	0·74	0·90	0·61	0·62	0·70	0·91	1·09

Comparing ordinary and quiet day Kew results in Table LXII., we see that the seasonal variation of m is less for ordinary than for quiet days. In summer the values are closely alike, but in winter the quiet day value of m is considerably the larger.

Lastly, comparing the corresponding results in Table LXII., for the range and the average departure from the mean, we see that in all cases the value of m for the average departure is markedly the larger. This signifies that large as are the changes in the range of the magnetic elements, they supply an underestimate of the average influence of sunspot frequency throughout the twenty-four hours.

Table LXIII. gives values for $100m$ at Pavlovsk and Katharinenburg for the ranges of the diurnal inequality from the eleven-year period 1890–1900. They were calculated in the same way as the values for Kew in Table LXII. The Katharinenburg results are only for "all" (a) days; for Pavlovsk "quiet" (q) day results are also given, except in the case of I.

There is the same conspicuous difference between winter and summer that was seen at Kew and Falmouth. The difference between the winter and summer values of m for D and H at Pavlovsk is also, as at Kew, greatest on "quiet" days.

TABLE LXIII.—*Values of* 10^2m *at Pavlovsk and Katharinenburg.*

Season.	Pavlovsk.							Katharinenburg.			
	D (*a*).	*D* (*q*).	*I* (*a*).	*H* (*a*).	*H* (*q*).	*V* (*a*).	*V* (*q*).	*D* (*a*).	*I* (*a*).	*H* (*a*).	*V* (*a*).
Winter	0·81	1·39	1·43	1·77	1·83	4·30	0·61	0·61	1·20	1·30	2·86
Equinox	0·76	0·68	1·07	0·95	0·94	2·93	0·83	0·68	1·24	1·15	1·67
Summer	0·52	0·52	0·90	0·98	0·71	2·18	0·50	0·49	0·87	0·83	1·24

In the case of V, however, at Pavlovsk the seasonal difference is most marked in "all" days, and the absolute value of m for "all" days is much in excess of that for "quiet" days at all seasons. This excess of the "all" day value is not due to the "quiet" day value being exceptionally small, but to the extraordinary size of the "all" day value itself. As the "all" day value for Katharinenburg is, though less, also very large, the phenomenon while probably exceptionally prominent at Pavlovsk is not peculiar to that station.

Table LXIV. gives values obtained for $100m$ at various stations, making use of the range in the mean diurnal inequality for the whole year, instead of the arithmetic mean range for the twelve months. The letters a and q have their usual meaning. The stations are arranged in order of latitude. The values obtained

TABLE LXIV.—*Values of* 10^2m *from Mean Diurnal Inequality for the Whole Year.*

Place.	Range.				Average departure from mean.			
	D.	*I.*	*H.*	*V.*	*D.*	*I.*	*H.*	*V.*
Pavlovsk (*a*)	0·70	1·01	1·02	3·26	—	—	—	—
,, (*q*)	0·69	—	0·95	0·46	—	—	—	—
Katharinenburg (*a*) ...	0·65	1·13	1·09	1·37	—	—	—	—
Irkutsk (*a*)	0·74	0·90	1·04	1·09	—	—	—	—
Kew (*q*)	0·71	1·45	1·07	0·56	0·87	1·75	1·39	0·57
Falmouth (*q*)...	0·83	—	1·13	—	1·03	—	1·37	—
Parc St. Maur (*a*) ...	0·59	1·16	1·06	0·60	—	—	—	—
Batavia (*a*)	0·72	0·61	0·71	0·52	0·85	0·72	0·77	0·65
Mauritius (*a*)	0·40	—	0·64	0·58	0·49	—	0·60	0·44

for m in the case of D are comparatively alike, except at Mauritius. The values obtained in the case of H are also very similar at the northern stations; they are decidedly larger than the corresponding D values, except at Batavia.

The closeness with which Wolf's formula represents the facts may be judged from a comparison made between observed and calculated values at the stations included in the previous tables. Excluding Mauritius, where the agreement was less good than elsewhere, and taking the case of the mean diurnal inequality for the whole year, the probable error in the calculated range—whether of D, H, or I—averaged about 6 per cent. of the total amplitude of the variation during the period concerned. The agreement was on the whole best in the "all" day results at Pavlovsk. The excess there of the largest over the smallest range during the eleven years considered was $3'{\cdot}62$ for D, and 16γ for H. The mean difference between the eleven observed and calculated values was $0'{\cdot}21$ in D, and $0{\cdot}8\gamma$ in H, the corresponding "probable errors" being respectively $0'{\cdot}19$ and $0{\cdot}7\gamma$. In the case of H, the difference between the observed and the calculated value exceeded 1γ on only one year, when it was 2γ. The average difference between the observed and the calculated range of I at Pavlovsk was only $0'{\cdot}043$, and the largest difference only $0'{\cdot}10$, though the largest of the annual values exceeded the least by $0'{\cdot}96$. The agreement between observed and calculated ranges was by no means so good for V as for the other elements.

Owing to absence of data, comparatively little can be said as to whether the a and b of Wolf's formula differ at different epochs. Signor Rajna,[1] considering D ranges obtained at Milan between 1836 and 1900 from daily readings at 8 a.m. and 2 p.m., calculated values for

[1] *Rend. del R. Ist. Lomb.*, 1902, Series II, Vol. 35.

a and b from the fifty-nine years, 1836 to 1894, and the twenty-four years, 1871 to 1894, separately. His results gave for $100m$, 0·89 from 1836 to 1894, and 0·87 from 1871 to 1894. The difference here is practically nil. The differences, however, between the observed ranges and those calculated by Rajna were almost all of one sign during certain sub-periods of years. Taking these shorter periods separately, I calculated values of a and b for them independently, as well as for the eleven years 1890–1900. The resulting values for $100m$ were for 1837 to 1850, 0·64; for 1854 to 1867, 1·03; and for 1890 to 1900, 0·94. These figures suggest that fluctuations do occur in the value of m. The value derived from 1890 to 1900, it will be noticed, did not differ much from that derived by Rajna from his longest period.

At Greenwich diurnal inequality ranges in D and H from 1841 to 1886 have been published by Mr. W. Ellis.[1] The following values for $100m$ have thence been calculated :—

TABLE LXV.—*Values of* 10^2m *at Greenwich for Different Epochs.*

Element.	1841 to 1896.	1865 to 1896.	1889 to 1896.	
	o.	*o.*	*o.*	*q.*
D.	0·52	0·56	0·62	0·65
H.	0·72	0·91	0·92	0·85

As usual o and q denote ordinary and quiet days. These figures suggest an increase in m during the later years, especially in the case of H. The values of the H ranges, however, in the earlier years seem to have suffered from temperature uncertainties.

[1] *Phil. Trans.*, **171**, p. 541; *Proc. Roy. Soc.*, 1898, **63**, p. 64.

One point to be remembered is that during so long a period as that covered by the Greenwich and Milan observations, the secular changes are considerable. Owing to changes in the magnetic meridian, the direction of the forces to which changes in D or in H are to be ascribed altered in either case by several degrees, and the force required to produce a change of $1'$ in D increased by several per cent.

CHAPTER XVI

NATURE OF SUNSPOT RELATIONSHIP

THE range of the diurnal inequality is not the only magnetic quantity that varies with sunspot frequency. Table LXVI. gives for each of the eleven years 1890–1900 Wolfer's sunspot frequency, and also for both declination and horizontal force the values of the following magnetic quantities at Pavlovsk:

(A) range of the mean diurnal inequality for the year,

(B) mean of the absolute daily ranges for the whole year,

(C) mean of the twelve monthly ranges (difference between the two extreme values of the month),

(D) annual range (difference between the two extreme values of the whole year).

TABLE LXVI.—*Sunspot Frequency and Ranges at Pavlovsk.*

Year.	Sunspot frequency.	Declination Ranges.				Horizontal Force Ranges.			
		(A).	*(B).*	*(C).*	*(D).*	*(A).*	*(B).*	*(C).*	*(D).*
		′	′	′	′	γ	γ	γ	γ
1890	7·1	6·32	12·1	28·2	42·1	22	49	118	169
1891	35·6	7·31	16·0	46·3	92·3	30	70	218	550
1892	73·0	8·75	21·0	93·6	194·0	37	111	698	2416
1893	84·9	9·64	17·8	48·3	87·1	38	79	241	514
1894	78·0	8·58	20·4	84·1	145·6	38	97	493	1227
1895	64·0	8·22	18·1	47·4	73·9	33	80	220	395
1896	41·8	7·39	17·5	52·4	88·7	29	74	232	574
1897	26·2	6·79	14·6	43·8	101·1	26	61	201	449
1898	26·7	6·25	14·7	46·6	118·9	26	67	276	1136
1899	12·1	6·02	13·1	38·3	63·8	24	58	178	382
1900	9·5	6·20	10·5	32·8	94·2	22	44	134	457

Sunspot frequency rose rapidly from 1890 to 1893, and then declined continuously until 1900, except that the value for 1898 slightly exceeded that for 1897.

In the columns (*A*) the parallelism to the sunspot variation is very close. In the columns (*B*), 1893, the year of sunspot maximum, is decidedly surpassed by the two adjacent years, and slightly by 1895; but on the whole the general parallelism with sunspot frequency is conspicuous. In the columns (*C*), 1893 falls more decidedly behind 1892 and 1894, though still retaining the fourth place. In the columns (*D*), 1893 lags far behind the leading years, and falls to the eighth place in the case of declination. As 1893 recedes, 1898 advances, until in columns (*D*) it takes the third place. The ranges in columns (*C*) depend on less than twenty-four of the principal storms, while those in columns (*D*) depend on one or at most two of the largest storms of the year. Table LXVI. shows that the size of the principal disturbances of a year cannot be inferred from the mean sunspot frequency of the year. A year of sunspot maximum may be in no way remarkable as regards its largest disturbance.

It must be remembered that sunspot frequency varies from day to day, and may be higher on several individual days of one year than on any single day of a second year whose average frequency is higher. Thus the phenomena exhibited in columns (*C*) and (*D*) are not necessarily incompatible with the view that the range and magnetic frequency on individual days are related to one another.

Though we could not safely infer it from Table LXVI., as a matter of fact 1893 was conspicuous rather from the absence than the presence of large or irregular disturbances. This may be seen on consulting Table LXVII., which gives an analysis of the absolute daily declination ranges at Kew similar to that in Table XXXI., p. 90, except that the years are treated separately and not the months of the year. The data in the two last lines of the

table are respectively representative of sunspot minimum and sunspot maximum.

TABLE LXVII.—*Sunspot Frequency and Kew Absolute Daily Ranges.*

Year.	0′ to 5′.	5′ to 10′.	10′ to 15′.	15′ to 20′.	20′ to 25′.	25′ to 30′.	30′ to 35′.	35′ to 40′.	Over 40′.
1890	12	161	155	25	10	1	1	0	0
1891	16	77	157	69	29	5	5	5	2
1892	2	42	132	108	35	16	14	2	15
1893	5	47	124	132	37	11	6	2	1
1894	2	53	159	88	27	13	4	6	13
1895	6	57	136	99	32	18	14	3	0
1896	14	71	157	61	34	15	5	4	5
1897	19	116	155	45	21	5	1	1	2
1898	21	122	149	40	22	6	2	0	2
1899	35	123	147	39	10	6	2	2	1
1900	56	176	117	8	4	2	2	0	0
Yearly averages—									
1890–1900	17	95	144	65	24	9	5	2	4
1890, 1899, 1900	34	153	140	24	8	3	2	1	0·3
1892–1895	4	50	138	107	33	14	9	3	7

For ranges from 15′ to 25′, the year 1893 holds its own with 1892 and 1894, but it is absolutely nowhere compared to them for ranges over 40′. Ranges under 10′ increase notably in number as sunspot frequency falls off. Ranges between 10′ and 15′ are about equally common in years of many and few sunspots. Ranges above 15′ are considerably more numerous in the average year of high than in the average year of low sunspot frequency, but the incidence of ranges over 30′ is extremely irregular.

Table LXVIII. shows the results of an attempt to discover what relation, if any, can be traced between magnetic conditions and sunspot frequency on the same day. During the eleven years 1890 to 1900 the magnetically quiet days selected by the Astronomer Royal numbered 660. Speaking generally, the less disturbed a day is, the smaller is the absolute range of any magnetic element. The mean absolute D range at Kew for the 660 selected

"quiet" days was only 9′·61, as compared to a mean of 13′·57 for all the days of the eleven years. If then any close relation exists between sunspot frequency and magnetic conditions *on the same day*, one would expect the average sunspot frequency from the selected "quiet" days to be notably below that for "all" days.

TABLE LXVIII.—*WOLFER'S Provisional Sunspot Frequencies*, 1890 *to* 1900.

	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Mean.
"All" days ...	40·1	40·4	35·6	41·2	43·5	45·3	45·4	45·7	45·6	41·6	32·4	35·6	41·03
"Quiet" days...	47·6	42·0	30·0	39·8	42·2	43·3	42·3	47·4	45·7	41·1	35·1	37·3	41·15

Table LXVIII. gives corresponding mean sunspot frequencies for "all" days and for the 660 "quiet" days, the different months of the year being treated separately. The sunspot data were taken from the lists of *provisional* frequencies published quarterly by Prof. Wolfer of Zurich in the *Meteorologische Zeitschrift.* These provisional frequencies are not quite so exact as the finally accepted values published later by Wolfer, but the differences are usually small and of an "accidental" character.

While there are sensible differences in individual months between the two sets of frequencies in the table, neither shows any decided excess over the other. The excess in the final mean, such as it is, rests with the "quiet" days. The result may be regarded as wholly negative.

Table LXIX. refers to a second attempt. The Astronomer Royal publishes particulars of the total area of the sun covered daily by sunspots. The days of each month of the eleven years 1890 to 1900 were divided into three groups, *A*, *B*, and *C*. In a month of thirty days *A* contained the ten days of largest spot area, *C* the ten days of least area, and *B* the intermediate days. During 1890, 1899 and 1900, nineteen months were omitted as containing each more than ten days free from sunspots.

The days of each year were with this exception arranged in the three equal groups *A*, *B*, and *C*, and it was investigated what proportion each of these three groups contained (i) of the Astronomer Royal's "quiet" days, and (ii) of the 209 days which had been selected at Kew as highly disturbed.

TABLE LXIX.—*Relation of Quiet and Disturbed Days to Sunspot Areas.*

Year.	Number of quiet days.			Number of disturbed days.		
	A.	*B.*	*C.*	*A.*	*B.*	*C.*
1890	5	6	4	0	0	0
1891	19	18	23	4	11	6
1892	17	23	20	8	16	6
1893	20	16	24	6	2	3
1894	20	18	22	10	7	4
1895	21	21	18	4	6	9
1896	22	18	20	15	11	11
1897	18	22	20	5	2	7
1898	16	23	21	8	7	4
1899	14	21	10	6	3	8
1900	7	9	9	2	0	0
Totals ...	179	195	191	68	65	58

Table LXIX. gives the results. If disturbance and sunspot frequency on the same day had been absolutely unconnected, what we should have expected to find—going to the nearest unit—would have been 188 "quiet" days and 64 disturbed days in each of the three groups. There is a deficit of "quiet" days and an excess of disturbed days in the group *A* of days of highest sunspot frequency, and conversely a deficit of disturbed days in the group of least sunspot frequency. But the deficits and excesses seem very small in view of the fact that the average day of group *A* had a sunspot frequency 5·2 times that of the average day of group *C*. Further, the group *B* of days of intermediate sunspot frequency contains more "quiet" days than group *C*, and only three fewer disturbed days than group *A*. Thus,

while there is some evidence of a relation between sunspot area and magnetic condition on the same day, the relation, if existent, would seem to be exceedingly small.

On the theory advanced by Prof. Svante Arrhenius,[1] magnetic disturbances on the earth are due to the projection of negatively charged particles from the sun, the time required to travel from the sun depending on the size of the particle, but most probably not exceeding two days. On this hypothesis, one would expect a relationship between magnetic conditions and the sunspot area one or two days earlier. Tables LXX. and LXXI. give some of the results of attempts to test this theory.

The ten days of largest sunspot area in each month of the eleven years 1890–1900 were got out. Taking each of these days, the absolute D range at Kew was written down for the day and the three following days. We had thus for each month ten ranges corresponding to the ten days of largest sunspot area, ten ranges corresponding to days following one day after the days of largest sunspot area, and so on. The algebraic excess of the mean range from each of these ten-day groups was then taken over the mean from all days of the month. This having been done for each month of a year, the mean excess was then found for the whole year, and finally for the whole eleven years. An exactly similar process was carried out in connection with the ten days of least sunspot area in each month. Table LXX. gives the mean results obtained for 1894, 1895 and the whole eleven years. The mean excesses of range for the eleven years are also expressed as percentages of the mean absolute range from all days.

Let us first consider what would be likely to happen if magnetic conditions on the earth were closely connected with sunspot area two days previously. The range would clearly be above the average on the group of

[1] *Terrestrial Magnetism*, Vol. 10, p. 1.

TABLE LXX.—*Algebraic Excess of Range over the Mean for the Period.*

—	Days of largest spot area.				Days of least spot area.			
	Same Day.	1 Day after.	2 Days after.	3 Days after.	Same Day.	1 Day after.	2 Days after.	3 Days after.
	′	′	′	′	′	′	′	′
1894	+1·23	+1·55	+1·61	+1·69	-1·44	-1·92	-1·62	-1·36
1895	-0·85	-0·22	+0·06	-0·17	+1·19	+1·41	+1·29	+0·92
11-year mean	+0·17	+0·25	+0·48	+0·53	-0·32	-0·45	-0·38	-0·35
Do. as percentage .	+1·5	+1·5	+3·2	+3·6	-2·1	-3·2	-2·7	-2·5

days which followed two days after the days of largest sunspot area of the month, and below the average on the group of days which followed two days after the days of least sunspot area. Moreover, as the sunspot area for the ten days of largest area was on the average fully five times that for the ten days of least area, we should expect the mean magnetic ranges in the groups specified to be the one notably above, the other notably below the average range. This is what actually happened in 1894. In the group answering to two days after the days of largest sunspot area the excess of range is 1′·61, and in the group answering to two days after the days of least area the deficiency of range is 1′·62. If all the years had resembled 1894, the evidence of connection would have been very strong indeed. At the same time, the excess of range in 1894 is not confined to the group of days which followed two days after the days of largest range, and similarly the deficiency is not confined to the group which followed two days after the days of least range.

Thus the natural conclusion to be drawn from the phenomena of 1894 would be that magnetic conditions are related almost equally to the solar conditions on the same day, and on each of the three previous days, and possibly to days considerably more than three days previous. The average results

from the whole eleven years point in the same direction as the results from 1894, but the apparent size of the sunspot influence on magnetic range is much less. There were, however, individual years, notably 1895, which associated large magnetic ranges not with large but with small sunspot areas.

Before passing from Table LXX. it should be explained that the percentages in the last line were not derived directly from the ranges in the line above, but represent the mean of percentage figures calculated for each of the eleven years.

Table LXXI. gives the results of an analogous investigation in which groups were made up of the ten days of largest and the ten days of least declination range for each month, and sunspot areas were found for the corresponding days and for groups of days earlier respectively by one, two, and three days. The unit in the sunspot areas ("projected" areas) is the one-millionth of the sun's apparent disk. The mean value of this area for the eleven years was 812. The figures in the table are the algebraic differences from the mean for the year or years concerned.

TABLE LXXI.—*Algebraic Excess of Sunspot Area over the Mean for the Period.*

—	Days of largest range.				Days of least range.			
	Same Day.	1 Day before.	2 Days before.	3 Days before.	Same Day.	1 Day before.	2 Days before.	3 Days before.
1894	+170	+147	+127	+108	−177	−187	−179	−165
1891	− 13	− 24	− 19	− 12	+ 31	+ 82	+ 53	+ 22
11-year mean	+ 35	+ 39	+ 41	+ 48	− 37	− 38	− 48	− 49
Percentages..	+ 4·4	+ 5·1	+ 4·9	+ 6·8	− 2·5	− 2·9	− 5·1	− 6·4

The percentages in the last line of the table are again means from percentages calculated for individual years. The means from the whole eleven years combined point in the same direction as those in Table LXX. The apparent

sunspot influence on magnetic range seems to increase up to at least the third day after. As in Table LXX., the year 1894 supported the hypothetical relation strongly, while 1891 pointed, though less markedly, to the diametrically opposite conclusion. The percentage differences in Table LXXI. are considerably larger than those in Table LXX. The mean ranges from the groups of days of largest and of least declination range were widely different, being respectively 19′·64 and 8′·99, a fact to be borne in mind when considering the significance of the percentage figures.

The investigation just described was repeated with this modification, that the groups of days of largest and least declination range contained each five days only. Also sunspot areas were taken for *six* successive days, extending from four days before to one day after the day to which the declination range belonged.

TABLE LXXII.—*Algebraic Excess of Sunspot Area over the Mean.*

Means for group of days.	1 Day after.	Same Day.	1 Day before.	2 Days before.	3 Days before.	4 Days before.
Of largest range	+ 4	+40	+59	+67	+72	+86
,, least ,, ...	−52	−64	−59	−60	−32	−35

Table LXXII. gives the mean results from the eleven years, the unit of sunspot area being as before. The figures are algebraic differences from the eleven-year mean value. The mean declination ranges for the two groups of days were respectively 23′·76 and 8′·15. The difference between these ranges is naturally considerably greater than in the case of the ten-day groups. Thus if the sunspot-magnetic connection is real, the excess of sunspot area for the first group and the deficiency for the second ought to be materially greater in Table LXXII. than in Table LXXI. This is actually the case in all the figures relating to the days of largest range, and in the figures relating to the same

day, and to one and two days before the days of least range.

Another feature in Table LXXII. favourable to the supposed connection is that the mean sunspot area for the day after the largest declination range is almost normal.

On the other hand, the fact that the sunspot area is nearly as much below the mean on the representative day following a specially "quiet" day as on the actual day itself, or the two days immediately preceding it, is at first sight a difficulty. One can scarcely suppose that what happens on the earth is due to what happens on the sun the day after. A possible explanation lies in the fact that days of few sunspots usually occur in groups, so that a day deficient in sunspots is more likely to be preceded by a day which is also deficient than by one which is normal. But days of large sunspot area also tend to occur in groups, and the corresponding phenomenon does not seem to occur in that case.

Besides assembling the results from the two groups of days for individual years, they were also assembled for the twelve months separately. A majority of months, including February, March, June, July, August, September and December, associated large sunspot area with large declination range; but in some months there was no decisive difference between the two groups of days, while in January and October a large sunspot area was associated with small declination range, not large.

When eleven-year means for December and September point in one direction, and those for January and October in the opposite, while 1894 and 1898 are opposed to 1895, and 1897 and 1899 appear neutral, the question must be regarded as not finally settled.

During the investigation a number of special cases were noted which seemed inexplicable except on the hypothesis that magnetic disturbances may arise on the earth which have no connection with the sunspot condition visible on

the sun either on the same day or several days previously. The following are examples :—In August 1890, the day of largest *D* range and the three immediately preceding days were alike free from sunspots. In April 1894 the two days of largest range were the days of least sunspot area for the whole month, and in each instance the four days immediately preceding were included in the group of days of least sunspot area. In October 1897, the day having the second largest range—a day, moreover, of considerable disturbance—and the four immediately preceding days formed five out of the eight days of the month which were free from sunspots. In February 1899 there were only three highly distributed days, one with a range over 45′, and all three were free from sunspots, though sunspots existed on seventeen of the twenty-eight days. In 1900 there was no measurable sunspot area from November 24 to December 31. But the daily declination range in December varied considerably, the mean from the five days of largest range being three and a half times that from the five days of least range.

In other cases unusually quiet magnetic conditions synchronised with large sunspot areas. Thus February 1, 1893, was an exceptionally quiet day, the declination range being 3′ less than that of any other day of the month. It posessed, however, the absolutely largest sunspot area of the month, and each of the four immediately preceding days had larger sunspot areas than any February day. Similarly, in February 1896, the two days of largest sunspot area were amongst the five quiet days selected by the Astronomer Royal, and their ranges were the smallest of the month.

The conclusion which I drew in 1908 from these facts was that unless a time lag exceeding one month be allowed, there must be agencies not associated with visible sunspots which powerfully affect the range of the magnetic needle. The sun may be the source in all cases, but only if the

presence of a visible sunspot at the time or for some days previously is not an essential feature. There is nothing in the phenomena described that seems decisive against the hypothesis that sunspots and magnetic disturbances may arise from a common cause operating throughout the solar system, but with an intensity which on one and the same day may be widely different on the sun and the earth. It must also be remembered that phenomena may be happening on the side of the sun remote at the moment from the earth, of which we know nothing, and we are not entitled on our present knowledge to rule these out.

On the theory of solar origin, a possibility to be borne in mind is that the ions, electrons, emanations, or whatever the vehicle of solar influence may be, may possess properties which decay only gradually in the earth's atmosphere. Thus on any given day the condition of that portion of space—if external to the earth—whence originate the immediate causes of movements regular and irregular of the magnetic needle, may be represented by an integral receiving finite contributions from a number of previous days. Such a possibility is suggested by the fact that in years of large sunspot frequency the daily magnetic range is persistently large, though on many individual days sunspots are only moderately represented.

On the other hand, highly disturbed magnetic conditions seldom last more than four days, usually considerably less, and "quiet" days often follow within three days after large disturbances. Also magnetic storms often reach great intensity, sometimes their maximum intensity, within a few hours after a prolonged quiet or but slightly disturbed period. Thus the immediate cause of at least some forms of magnetic disturbance must be something capable of very rapid changes and having no very prolonged period of decay.

Reference was made on p. 157 to the diurnal variation in the frequency of commencements of magnetic storms

at Greenwich. This frequency seems to follow decidedly different laws in years of many and of few sunspots, as may be seen by reference to Table LXXIII.

TABLE LXXIII.—*Diurnal Distribution of Commencements of Storms at Greenwich.*

	All storms.			"*M*" storms.		
	0–11 a.m.	Noon to 7 p.m.	8–11 p.m.	0–11 a.m.	Noon to 7 p.m.	8–11 p.m.
Sunspot maximum	29	52	19	21	58	21
,, minimum	19	68	13	14	75	11

The table gives the number of commencements in the three specified parts of the day, expressed as percentages of the total number. Results are given both for all Mr. Maunder's storms and for those of lesser amplitude included in his class *M.* The two groups of years were respectively constituted of three successive years at each maximum of sunspots, and three successive years at each minimum.

Even in the sunspot maximum years, the concentration of the commencements in the afternoon hours is striking, but it is by no means so outstanding as in the case of the sunspot minimum years. The concentration in the afternoon is greater for the lesser (*M*) disturbances.

The annual distribution of storms at Greenwich seems also influenced by sunspot frequency. This is shown by the figures in Table LXXIV., which expresses the number for each of the three seasons as a percentage of the total for the year. All the storms in Mr. Maunder's tables were included.

TABLE LXXIV.—*Annual Distribution of Storms at Greenwich.*

	Winter.	Equinox.	Summer.
Sunspot maximum	35	38	27
,, minimum	28	48	24

Taking the fifty-six years covered by Mr. Maunder's investigation, equinox possessed considerably more than its fair share—one third—of the disturbances. Table LXXIV. shows that this peculiarity of the equinoctial months is much more prominent in years of few than in years of many sunspots. It would appear that at Greenwich as sunspots increase the incidence of prominent magnetic disturbance tends to be more uniform, alike throughout the twenty-four hours and the twelve months.

CHAPTER XVII

GENERAL CONCLUSIONS

Secular Change.—Chapter II presents the facts of secular change in a way intended to facilitate the study of the general phenomenon. The data serve, however, in addition, the practical object of enabling an estimate to be made of the present value of the magnetic elements at places where observations have been made at some previous time. The ultimate source of our knowledge of the magnetic elements at most places in the British Isles is the great survey for the epoch 1891, due to the private enterprise of Sir Arthur Rücker and Sir T. E. Thorpe. The time elapsed since that epoch is so long that a comparatively small error in the mean annual change assumed becomes serious. It is thus important to consider the available sources of information as to secular change.

From 1891 to 1901, when observations began at Valencia, there were no systematic observations in Ireland, and until 1908 when Eskdalemuir was instituted there were none in Scotland, or in England north of Stonyhurst. So far as the writer knows, the only published data of importance, except those from the stations included in Table I., and from a station in Jersey, where observations were made for some years, are given in a paper by Commander L. W. P. Chetwynd[1] published in 1909. The data discussed by Commander Chetwynd

[1] *Phil. Trans.*, *A* 209, p. 227.

represent observations made in 1907 under the auspices of the Hydrographic Department of the Admiralty, at twelve of the stations of the 1891 survey, including six in England and Wales, four in Scotland, and two in Ireland.

The declination results deduced by Commander Chetwynd are mostly very similar to the corresponding results for Kew. At Kirkwall a distinctly larger change was observed, but further evidence would be needed to justify the assumption that this is true of the whole north of Scotland. The secular changes deduced for the other elements presented greater divergences.

Those familiar with the subject will probably allow that it is desirable that more systematic provision than hitherto should be made in this country for securing secular change results. If, as some of the data in Chapter II and in Commander Chetwynd's lists suggest, there are changes peculiar to small areas, in addition to the general secular change which is nearly uniform over large areas, the only really satisfactory plan is probably to have a general survey repeated at regular, comparatively short intervals, like a census. Changes, if such there be, due to alterations of magnetic strata of limited extent, at no great depth, can be investigated only by employing numerous stations. In highly disturbed regions the possibility of such changes can hardly be safely neglected. In the British Isles, however, local disturbances are mostly small, and it seems not improbable that secular change data adequate for most practical purposes can be derived from a comparatively small number of well chosen stations.

A good deal could be done if educational institutions, possessed of the necessary instruments and observers, co-operated in a general scheme of systematic observations. Perhaps the chief obstacle to such a scheme is the necessity of observing at a distance from large artificial electric currents. Any co-operating institution would have to occupy some site in the open country. It would be

desirable to have a small permanent wooden hut, free from iron, with some suitable distant mark of assured fixity, whose azimuth could be determined once for all. If a few such structures existed at well selected places, and observations were made annually on some pre-arranged day or days, the different magnetic elements being observed in a uniform way, at pre-arranged hours, by observers having the necessary skill, a substantial step would undoubtedly be taken to maintain the utility of Rücker and Thorpe's survey.

The places, unfortunately, where knowledge of secular change is least satisfactorily provided for at present are remote from large centres. If we were to select three localities as specially important, they would be N.W. Connaught, the Hebrides, and Shetland (or Orkney). Supposing these districts provided for, the next in desirability would be S.E. Ireland (*e.g.*, Wexford), Antrim, or the Mull of Kintyre, and N.E. Scotland (Aberdeenshire). W. or S.W. Wales (Pembroke), East Anglia (Norfolk coast), and the Yorkshire coast are also sufficiently remote from existing observatories to make secular change observations there valuable; and Jersey, where observations were taken for some years by the Jesuit Fathers, would make a convenient stepping stone to France. At the present moment, S.W. England and S.W. Ireland are provided for by Falmouth and Valencia observatories, but if either of these ceased to exist, the loss would be serious.

Non-cyclic Change. We have seen in Chapter III that on the average "quiet" day there is a non-cyclic or aperiodic change, far too large to neglect when forming the diurnal inequality; and it was explained in Chapter IV that this was usually eliminated by assuming the change uniformly progressive throughout the twenty-four hours. Several difficult questions arise. The non-cyclic change shown by the curves is usually in part of instrumental origin. Magnetographs wholly free from "drift"

due to change in the magnet or suspension, uncompensated temperature effect or other cause, have still to be invented; and in some cases the instrumental drift is as large as the true non-cyclic change in "quiet" days. If a considerable time has elapsed since the instrument was touched, the instrumental drift, if unaffected by temperature changes or large magnetic storms, is likely to progress at a practically uniform rate; and it is thus theoretically possible, by comparing results from "quiet" and other days, to arrive at the true non-cyclic effect on the former. In practice, however, the exact determination of the true non-cyclic effect in individual "quiet" days is exceedingly difficult.

So far as concerns the diurnal inequality, it is immaterial whether the apparent non-cyclic change is due to natural or instrumental causes. The crucial point is whether it comes in at a uniform rate throughout the twenty-four hours. As already remarked, the instrumental contribution is likely to come in uniformly under certain conditions, but it unquestionably does not do so if due to viscosity in a recently fitted suspension. The true non-cyclic effect itself is hardly likely to come in at a uniform rate on individual "quiet" days. If it is a property inherent in quiet conditions—independent of what precedes the "quiet" day concerned—it will presumably have a varying rate of incidence, unless the day is uniformly quiet, which is seldom the case. If, on the other hand, it is a reaction from previous disturbance, it will naturally depend on the interval of time elapsed since the determining disturbance or disturbances. Thus, unless there have been a number of "quiet" days immediately preceding the day considered—an unusual circumstance—the influence in question may be expected to decay sensibly during the twenty-four hours. Again, as we have seen in Chapters VI, XI, and XVI, the phenomena of magnetic disturbances show a dependence on local time, which raises

a presumption that the same will be true of the non-cyclic change, if it is an associated phenomenon. The Kew curves since the discovery of the non-cyclic change have been regularly measured at the noons preceding and following all "quiet" days, with the view of eliciting information on this very point, but difficulties present themselves in interpreting the results. The two twenty-four-hour periods which respectively end and begin at the noon of a "quiet" day are frequently affected, one or both, by disturbances; the forty-eight hours centring at the noon of a "quiet" day can seldom be regarded as uniformly quiet.

As mentioned on p. 27, the non-cyclic change on the average "quiet" day at Kew equals about 10 per cent of the inequality range in H, and about 15 per cent in I. Thus the method of its elimination is of practical importance. If, however, it should prove that the non-cyclic change has a rate of variation depending on local time, there will be no difficulty in applying the necessary modification to inequalities got out in the usual way, provided a record is kept of the value of N in the formula on p. 33.

Diurnal Inequalities.—This is probably not the only uncertainty affecting diurnal inequalities based on the "quiet" days of individual months. No opportunity has arisen of determining the lunar day diurnal inequality at Kew for recent years, but the old investigations of General Sabine showed a very sensible lunar inequality there, and the same has been observed elsewhere. This inequality must be practically eliminated from the solar diurnal inequality derived from all days of the month, but the extent to which it is eliminated from a solar diurnal inequality based on only five days varies according to their choice. Results, however, such as those in this book, which depend on the "quiet" days of a number of years, are unlikely to be appreciably affected by this uncertainty.

In some months of some years, *e.g.*, the later months of

1900, the choice of "quiet" days is very large, and the five selected naturally exhibit a close approach to the ideal "quiet" day, when no irregularities are visible in the trace. But in highly disturbed years, *e.g.*, 1895, there are months in which as many as five days cannot be got without including days which one would not ordinarily accept as "quiet." There is thus a certain arbitrariness in the diurnal inequality deduced from "quiet" days, which forms a strong argument for an international choice and its general acceptance. Attention has already been directed in Chapter VI to the existence of a similar but much greater arbitrariness in diurnal inequalities derived from selected highly disturbed days. This arbitrariness, it is to be feared, must continue to exist until the relations between disturbance and the diurnal inequality have been much more fully investigated.

The diurnal inequalities for ordinary days at Kew in Chapter V embrace declination only, as corresponding data for the other elements were not available. Steps are being taken at the present moment to fill this gap. Another thing lacking is a comparison of inequalities from different epochs. Comparatively few observatories have records extending even twenty years back; so that imformation as to the presence or absence of secular change—as distinct from the eleven year period—in the forces to which the diurnal inequality is due, is practically non-existent. One difficulty in the way is the secular change in the magnetic elements themselves. At Kew, for instance, the mean values of D and H were respectively 20°58′·7 and 0·17662 in 1865, as against 17°16′·8 and 0·18278 in 1895. H and D diurnal inequalities represent the daily fluctuations of force respectively in and perpendicular to the magnetic meridian. Thus in 1865, ΔH represented a change of force in a direction 20°58′·7 west of north, while 1′ in ΔD implied the action of a force of $5{\cdot}14\gamma$ in a direction 20°58′·7 south of west. But in 1895, ΔH repre-

sented a change of force in a direction 17°16′·8 west of north, while 1′ in ΔD implied a force of $5{\cdot}32\gamma$ in a direction 17°16′·8 south of west. If then the diurnal inequalities from 1865 and 1895, for instance, appeared identical, ΔH being expressed as usual in *C.G.S.*, and ΔD in minutes of arc, the forces causing the regular diurnal variations of the two epochs were really different; and conversely, if the inequality forces remained unchanged, relative to axes fixed in the earth, the D and H diurnal inequalities would appear to alter.

This difficulty, it may be observed, is not wholly absent when we confine ourselves to individual years, or even to individual days. An extreme instance of this is afforded by the remark on p. 109, that in the course of twenty-two months at the Winter Quarters of the *Discovery*, there were at least seven days on which the extreme positions of the declination needle differed by more than 4°50′. What the changes in H may have amounted to on these occasions is unknown, owing to loss of trace, but they may well have represented 10% or more of the undisturbed value. In such circumstances the exact numerical interpretation of D and H changes in terms of force presents some difficulty.

There are thus some theoretical advantages in N. and W. inequalities, and possibly even in the use of magnetographs recording changes of force along geographically fixed directions, and this is especially true of Arctic and Antarctic stations. The advantages, however, are not all on one side. The troubles attending the working of a declination magnetograph are usually notably less than those of magnetographs registering force components, while for practical purposes declination is much the most important element. So far as ordinary results from individual years are concerned, the deduction of N. and W. inequalities from these for D and H, or the converse, is a very simple operation.

Disturbed Curves.—The curves reproduced in Chapters XI, XII, and XIII, with the exception of Fig. 18, have a time scale of 10 mm. to the hour, as compared with 20 mm. in the original Antarctic curves, and 15 mm. (more exactly 0·6 inch) in the curves from Kew pattern magnetographs. But, even allowing for this, it will be readily recognised how difficult it is to say exactly what are corresponding points in curves from different observatories, or even in the curves of different elements at one station, especially when there are incessant short period oscillations, as in Fig. 21*c*, p. 121. Even if we assumed that the disturbances seen at any instant all over the earth arise from a single force system, the turning points on the different curves would not necessarily synchronise. They must be influenced—usually, of course, only to a small extent—by the diurnal inequality forces, which depend on local time. In most cases there are probably a variety of sources of disturbance in operation at the same instant, some exerting a visible effect over only limited areas. If we compare, for instance, Figs. 23 and 24, which relate to the same occasion, we see practically no trace of disturbance on any one of the curves of Fig. 23 during a whole hour prior to 11.25 p.m. (23 h. 25 m.) on April 5, whereas in Fig. 24 the D and H curves during this time—though much quieter than later—show decided oscillations. Thus a sensible disturbing system must have been in operation in the Antarctic prior to the visible commencement of the magnetic storm in temperate latitudes, and there is no reason to suppose that this pre-existent system ceased when the universally felt magnetic storm began. Evidence pointing in the same direction is deducible even from the records of British stations. Kew and Falmouth records of magnetic storms are usually very similar, so much so that we might almost mistake them for duplicates; but in some cases, while the greater part of the traces shows this close resemblance, short portions of trace stand out as markedly different.

Magnetic Storms.—There is no side of Terrestrial Magnetism which appeals so much to the imagination as magnetic storms, and none presents equal fascination for theorists. It is difficult to get the ordinary man —even the ordinary scientific man—to recognise that in this, as in other cases, minute study of the facts ought desirably to precede speculation as to the cause of the phenomena. The attention of those predisposed to theorise may perhaps profitably be directed to curves such as those of Figs. 20*b*, 21, and 24 and the Antarctic traces in Figs. 25 to 42. It is easy to imagine, as some have done, swarms of electrons of one sign flying past the earth and altering the force components for the time being to one side of their normal value; but the deflections, more especially in high latitudes, may be now on this side now on that side of the normal, and the change from one side of the normal to the other may take place every few minutes, for an hour on end. Are we to imagine alternate swarms of positive and negative electrons laid on like jets of hot and cold water? It is essentially a case in which details cannot be treated as unimportant.

Some of the phenomena—*e.g.* the depression usually seen in H after magnetic storms—strongly suggest subpermanent changes in the earth's own magnetism, or the persistence and very slow decay of unidirectional electric currents set up by the storm. There is no reason to suppose that this phenomenon in H, for instance, exists only after the withdrawal of the forces causing the magnetic storm, quite the contrary. Thus during the progress of the actual magnetic storm, especially its later portions, the value of any element, at any given instant, is most probably dependent in part on the disturbing forces existing earlier. During the active portions of magnetic storms there are undoubtedly, as a rule, large earth currents in being, and our information respecting these is still very partial and incomplete. Thus a great deal may remain to be done before we can infer from the force systems

calculated from the observed magnetic changes the exact locus and magnitude of the disturbing force systems to which magnetic storms are ultimately due.

Sunspot Relations.—The existence of a relation between sunspots and Terrestrial Magnetism is widely known, but its character is usually misunderstood. The only parallelism that may be regarded as fully established is that between the mean sunspot frequency of the year or season—not of the individual day—and the range of the corresponding diurnal inequality of the magnetic elements. This relationship is discussed in Chapter XV., where it is shown that the range of the diurnal inequality increases, at least very approximately, directly as the increase in sunspot frequency, but that the proportional increase is not the same for the different magnetic elements. Thus we have, according to Table LXI., p. 169, for a rise of 100 in Wolfer's sunspot frequency number, a percentage rise in the range of the diurnal inequality for the year, derived from "quiet" days at Kew, of 45 in *V*, 63 in *D*, 89 in *H*, and 111 in *I*. It is also shown in Chapter XV. that the numerical relationship between sunspot frequency, or area, and diurnal inequality range varies with the season of the year, a given increase in sunspot frequency being associated at the stations considered with a larger proportional increase of range in winter than in summer.

Sunspot frequency and the range of the diurnal inequality have been observed to rise and fall together for the last sixty years, but it is at least open to doubt whether the numerical relationship between the variations of the two quantities has remained uniform.

It is shown in Chapter XIV. that the diurnal inequalities in years of many and of few sunspots differ in type as well as in range. Speaking generally, an increase in sunspots is associated with a reduced difference between the phenomena of day and night, and of summer and winter, in the magnetic diurnal inequality.

When it comes to irregular changes of the magnetic elements, it is shown in Chapter XVI. that an intimate connection with sunspots is much more open to doubt. Such evidence as there is of a relationship between sunspot area and absolute magnetic range on individual days, is more favourable to the view that the phenomenon on the earth is influenced by the state of the sun some days previously than on the actual day considered.

The question as to the direct relationship between large magnetic storms and individual sunspots is a difficult one. That there is such a connection is not merely a popular belief, but also the view of some authorities who have specially studied the subject. There are numerous instances of storms occurring when specially prominent spots were on the sun. On the other hand, notable storms have occurred when the spot area was below its mean, and some years at least of great sunspot development have been exceptionally free from large disturbances. For instance, 1893, a year of sunspot maximum, and characterised by exceptionally large ranges in the diurnal inequalities, was less disturbed than 1891 or 1896, years with less than half its sunspot frequency.

We may perhaps at present be in the same position as medical science would be in if no distinction were recognised between small-pox, chicken-pox and measles. In such circumstances the death rate from eruptive diseases might well appear arbitrary. Astronomers presently may find it possible to recognise different types of sunspots, and a magnetic relationship may then become conspicuous. In the meantime, it is probably the wisest course to keep an open mind as to the existence of a direct connection between sunspots and magnetic storms, or as to the nature of the relationship between solar and magnetic phenomena on individual days.

INDEX